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July 1993

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Flood Control Structures Research Program

Flow Impingement, Snake River, Wyoming

by Stephen T. Maynord
Hydraulics Laboratory

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Prepared for Headquarters, U.S. Army Corps of Engineers

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Research Program

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Flow Impingement, Snake River, Wyoming

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U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

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Washington, DC 20314-1000

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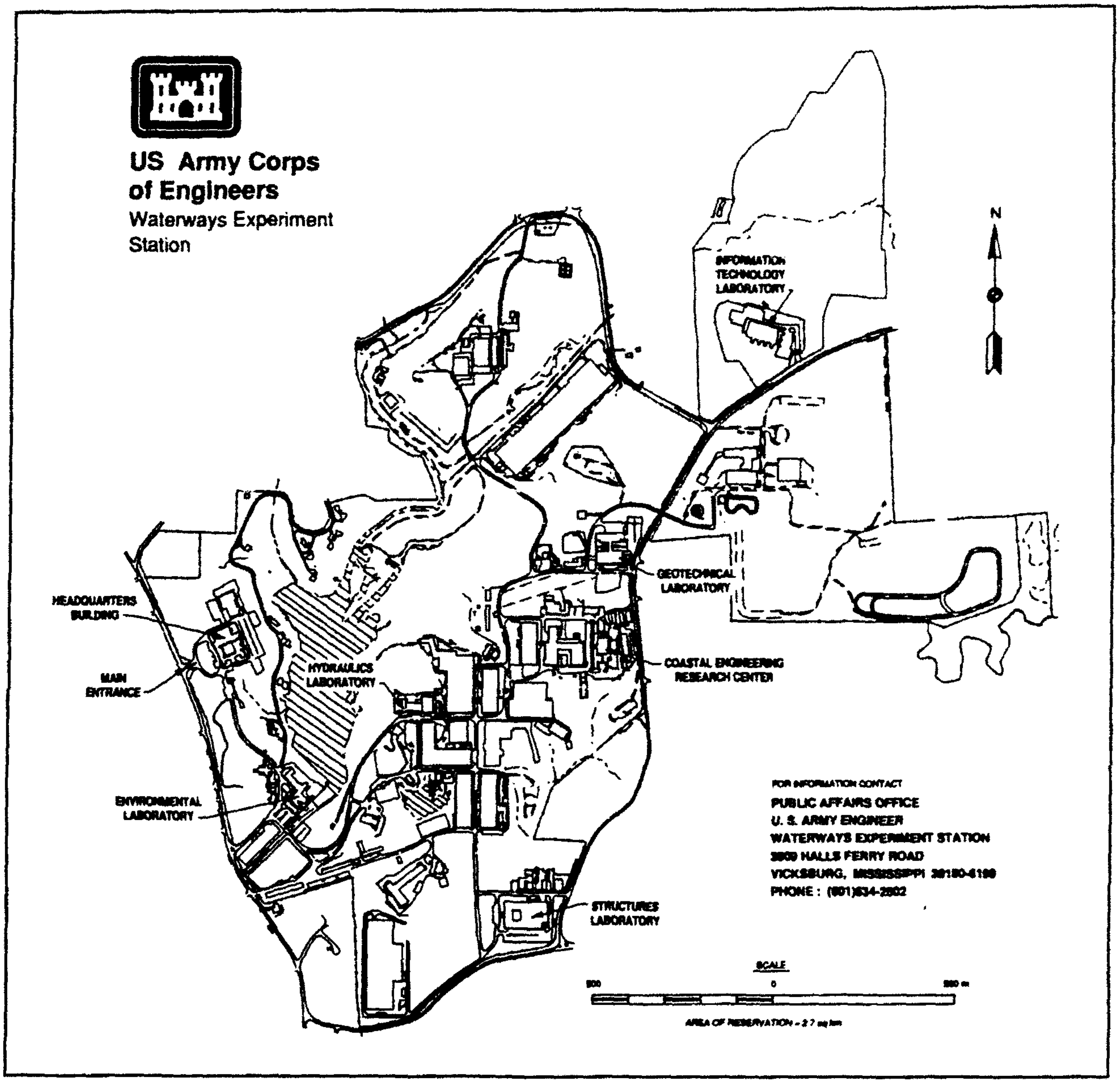

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
degrees (angle)	0.01745329	radians
feet	0.3048	meters
inches	2.54	centimeters
miles (U.S. statute)	1.609347	kilometers
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters

1 Introduction

Background

Many streams can be found in which the channel planform results in a high degree of hydraulic irregularity. A prime example is a braided planform in which multiple channels exist over a wide range of flow conditions. These multiple channels tend to migrate due to erosion and deposition processes typically found in alluvial channels. Migration rates can be quite rapid when upstream midchannel islands and bars are breached or when logjams give way. Channel migration often leads to flow being directed against bank lines at large acute angles, which is referred to herein as flow impingement. Flow impingement results in significant stress on the bank line, and channel protection is often required to maintain channels in a fixed position. The maximum attack often occurs at intermediate rather than high discharges because high discharges tend to submerge the midchannel islands and bars and the flow is more generally directed in a downstream direction. When stages exceed the tops of the midchannel bars, the channel area increases rapidly and velocities do not show the same rate of increase with stage. While the locations of flow impingement show some degree of regularity, entire channel reaches must often be protected because the locations of flow impingement cannot be predicted with enough certainty to leave some areas unprotected. At impingement sites, bank lines are subjected not only to high velocity but also to deep scour, and undermining of bank protection is a common occurrence.

An example where flow impingement is a problem is the Snake River near Jackson, WY (Figure 1), which is a braided stream with levees on one or both sides of the channel that are almost completely protected with riprap revetment. The levees in this reach average about 1,200 ft[1] apart. The river appears in some areas to meander between the levees, while in other areas the braided planform is evident. This upper reach of the Snake River has a slope of about 19 ft/mile and the peak runoff is snowmelt, which generally occurs in early June. A plot of discharge versus date for various exceedance percentages at the gage known as Below Flat Creek is shown in Plate 1. The mean peak discharge is about 12,000 cfs, and 90 percent of the years have a peak

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1 A table of factors for converting non-SI units of measurement to SI units is found on page v.

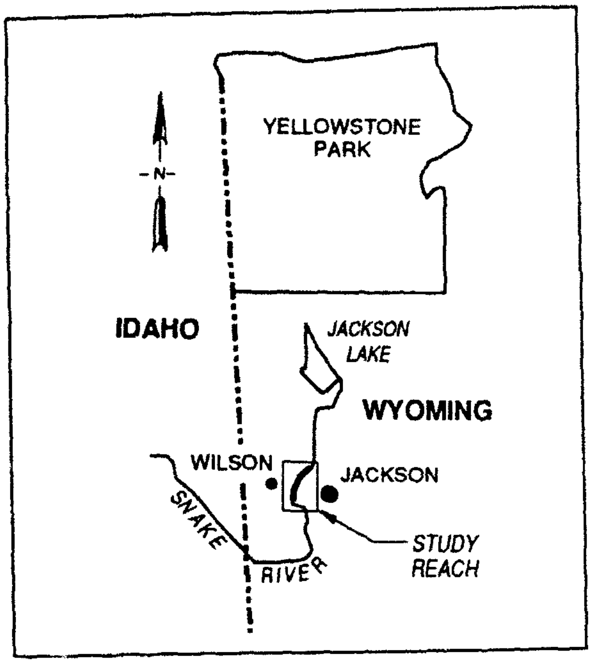

Figure 1. Location map

discharge of 18,000 cfs or less. In 1986, a major event occurred with a peak discharge of 25,600 cfs. The largest known flood occurred in 1894 with an estimated peak of 41,000 cfs. The bed materiai in this reach is sand and gravel ranging up to a maximum size of 6-10 in. Unfortunately, bed material gradation data are not available for this reach. The size of the riprap on the levees varies widely as does the unit weight of the stone. The larger stone in the riprap gradation is placed near the toe of the slope. The levee cross section presently used in this reach is shown in Plate 2.

Objective and Scope

The overall objective of this study is to develop guidance for design of riprap under flow impingement. The scope of the study reported herein was to observe and document the characteristics of flow impingement zones including nearbank velocities and depths, water-surface slopes, and alignments and to develop methods for estimating impinged flow velocities and scour in braided channels. Information obtained from this field study will be used to investigate riprap size in a physical model. This report presents details and information in addition to that given in Maynord.[1]

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[1] S. T. Maynord. (1992). "Flow impingement velocities, Snake River, Wyoming." *Hydraulic Engineering: Saving a Threatened Resource—In Search of Solutions; Proceedings, Hydraulic Engineering Sessions at Water Forum '92,* Baltimore, MD, August 2-6, 1992. Marshall Jennings, Nani G. Bhowmik, ed., American Society of Civil Engineers, New York, 139-144.

2 Description of Tests and Data

On 5 June 1991, the river was inspected and 14 areas of significant impingement were found in the project reach. Velocity measurements were made at eight of these sites, as shown in Figure 2. Future efforts of this type should also obtain aerial photographs of the project just before measurements are conducted.

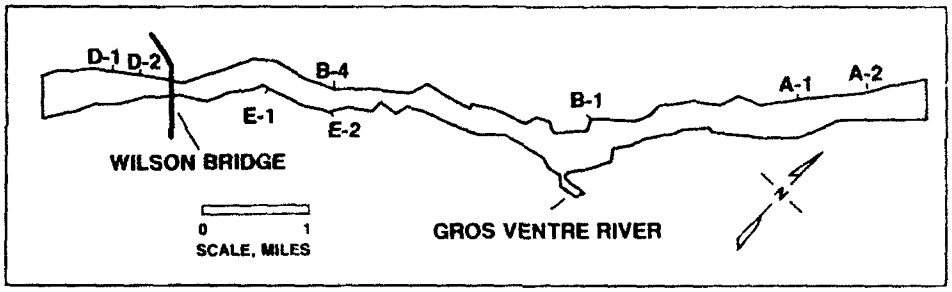

Figure 2. Snake River project reach and impingement sites

The measurements reported herein were collected between 6-8 and 10-12 June 1991, which was the peak runoff period for 1991. Plate 1 shows the mean daily discharge at Below Flat Creek on the Snake River for May, June, and July 1991. The mean daily discharge at Below Flat Creek (downstream of Wilson Bridge) was 14,000 cfs on 6 June, 14,500 cfs on 7 and 8 June, 15,000 cfs on 10 June, 15,500 cfs on 11 June, and 16,000 cfs on 12 June. The discharge began to fall on 13 June. Therefore, 1991 had an above-average runoff. The discharge near the mouth of the Gros Ventre River was about 2,100 cfs during 6-12 June 1991. The water-surface elevation during 6-12 June was near the top of many of the midchannel bars.

Price and electromagnetic velocity meters were mounted on lead fish and supported by an extendable boom crane that could reach up to 40 ft from the bank line, as shown in Figure 3. Even though the electromagnetic velocity meter could measure velocity in two directions, only the velocity parallel to the orientation of the lead fish was used in this investigation. Initially, a

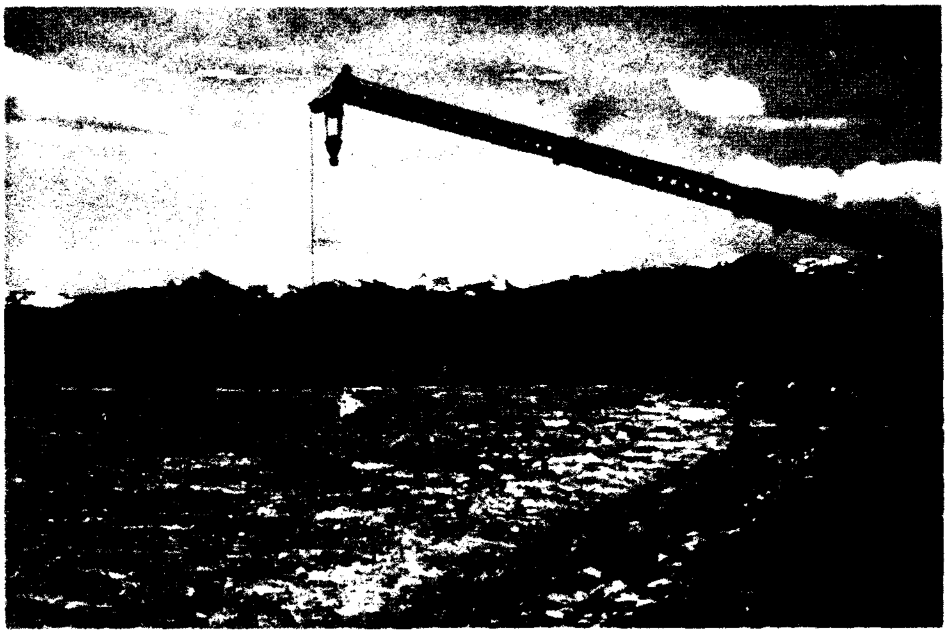

Figure 3. Crane at velocity site B-4, looking downstream

100-lb lead fish was used, but this was swept too far downstream and a second lead fish weighing 140 lb was attached below the first one.

Future studies should use a single 200- to 250-lb lead fish for the high velocities encountered in this study. When near the bank line in shallow depths, the lead fish exhibited erratic side-to-side movement, which made velocity and depth measurements difficult. A graduated tape was attached both horizontally and vertically to the cable supporting the meter to determine the position of the meter. Bottom position was noted when the fish hit bottom and the cable deflected. Future studies should consider some type of electronic depth meter. The velocity meter had to be frequently raised to prevent damage to the velocity meter from debris. The cable supporting the velocity meter should not be strong enough to pull the crane over if large debris hangs up on the meter.

The two types of impingement sites that were observed on the Snake River were dependent on the alignment of the levee. Velocity sites A-1, A-2, B-4, D-1, D-2, and E-1 were impingement sites where the levee was straight. Velocity sites B-1 and E-2 were sites in a curved part of the levee having a outer bank line radius of 300-500 ft. In most cases the typical site had a wide, shallow approach channel that gradually converged toward the impingement site. The angle of the approach flow ranged up to 70 deg. Plates 3-10 show schematics of the impingement sites. Figures 4-8 show impingement sites.

Velocities were taken at the apparent point of main attack (designated sta 5+00 with stations increasing in a downstream direction), and additional stations were taken upstream and downstream of that point. Water-surface

Figure 4. Site A-1, looking downstream

Figure 5. Site A-2, looking upstream

Figure 6. Site B-1, looking upstream

Figure 7. Site E-2, looking upstream

Figure 8. Site B-4, looking upstream

elevations relative to an arbitrary datum were measured upstream and downstream of sta 5+00 to establish water-surface slope. Water-surface elevations were measured at the bank line with a level rod. Plots of observed velocities at each site are shown in Plates 11-37. Water-surface profile plots are shown in Plates 38-47.

Comments about each site are presented in the order of the initial measurement as follows:

a. *Site E-1 (6 June 1991).* At site E-1, almost all of the riverflow was in a single channel against the levee, but the channel width was relatively large. This site was not so much an impingement as it was a concentration of flow on one side of the river. This was the initial measurement site and was chosen because velocities appeared to be low compared to the other sites. Velocities were taken at site E-1 with only the 100-lb lead fish, and water depth could not be determined with any confidence because of the large cable deflection in the downstream direction with the single fish.

b. *Site D-1 (6 and 12 June 1991).* At site D-1, almost all of the flow in the river was in a single channel against the levee. The impingement angle was about 40 deg, and a significant amount of flow was entering the impingement site from a second channel parallel to the levee. At this site, the single lead fish was swept too far downstream, and a second lead fish weighing 140 lb was added below the first fish and used for all remaining tests. The electromagnetic velocity meter was 18 in. above the bottom of the lower fish. This site had velocities up to

16 ft/sec, but the water-surface slope measured along the bank line did not show the large values measured at other sites, possibly because measurements were limited to 100 ft upstream of sta 5+00. Measurement of surface velocity based on surface debris yielded a velocity of 13 ft/sec between sta 4+00 and 6+00. The debris velocity was measured if its position relative to the bank was near the position of the maximum measured velocities. The channel bottom observed on 6 June is shown on the 12 June plot (Plate 32).

c. *Site A-1 (7 and 10 June 1991).* Most of the flow in the river was against the levee at this site, but some flow was in channels in the middle of the levees. The impingement angle was about 45 deg and flow was also entering the impingement site from a second channel parallel to the levee on 7 June with a lesser amount on 10 June. Surface float velocities about 30 ft from the bank line averaged 11 ft/sec between sta 4+00 and 6+00. Velocities and water-surface elevations were similar on 7 and 10 June, but some scour occurred between 7 and 10 June at sta 4+00. Measurement of riprap size at site A-1 showed an average W_{50} of about 150 lb. Riprap size was not measured at other locations, but surveys by the U.S. Army Engineer District, Walla Walla, in 1987 show the average size to be less than 100 lb.

d. *Site A-2 (7 and 10 June 1991).* At this site, a significant amount of the riverflow was in other channels away from the levee. The impingement angle at this site was about 60 deg. Surface float velocities on 7 June were about 13 ft/sec between sta 4+00 and 6+00. Significant differences in the flow impingement were evident from 7 June compared to 10 June indicating the dynamic nature of braided streams. Velocities measured on 10 June were 60-70 percent of those measured on 7 June, and the water-surface elevations had increased by up to 1.5 ft. The maximum impingement point had moved downstream about 200 ft. The cause of these changes was not apparent from the on-ground inspection.

e. *Site B-1 (8 and 11 June 1991).* A significant portion of the total riverflow was in channels away from the levee at this site. The large impingement angle of about 70 deg resulted from the curved levee alignment. Surface float velocities were as follows:

Sta	Velocity, ft/sec
3+00 to 4+00	9.0
4+00 to 5+00	11.0
4+50 to 5+50	12.0
5+00 to 6+00	12.5
5+50 to 6+50	11.0

Side slope velocities on 8 June were relatively large. Velocities at sta 4+50 were much smaller on 11 June than on 8 June indicating some type of change upstream.

f. *Site B-4 (8 and 11 June 1991).* Most of the riverflow was against the levee at this site. The flow impingement angle was about 50 deg on a relatively straight levee alignment. Surface float velocities were as follows:

Sta	Velocity, ft/sec
3+00 to 4+00	11.0
4+00 to 5+00	12.5
5+00 to 6+00	13.0
6+00 to 7+00	12.0

The bottom elevation on 8 June was not determined, and the bottom shown (Plates 27 and 28) is from the 11 June measurements. Water-surface measurements were similar on 8 and 11 June.

g. *Site E-2 (12 June 1991).* Most of the riverflow was against the levee at this site, and the curved levee alignment caused an impingement angle of about 60 deg. Surface float measurements were as follows:

Sta	Velocity, ft/sec
3+50 to 4+50	10.0
4+00 to 5+00	10.5
4+50 to 5+50	11.0
5+00 to 6+00	11.5
5+50 to 6+50	13.0
6+00 to 7+00	13.0

Sta 5+70 exhibited relatively large depths at the toe (15 ft) and high velocities up on the side slope (>12 ft/sec).

h. *Site D-2 (12 June 1991).* The flow approaching site D-2 was only a portion of the total riverflow, and the impingement angle was about 60 deg. Velocities were measured at only sta 5+00, and surface float velocities were as follows:

Sta	Velocity, ft/sec
3+00 to 4+00	9.0
4+00 to 5+00	11.5
5+00 to 6+00	12.5
6+00 to 7+00	12.0

Bottom elevations could not be detected with enough certainty to record values at this site.

A comparison of velocities at site A-2 was made between the electromagnetic velocity meter that was used in all of the other tests and a Price current meter. The Price meter measurements are shown in Plate 48. While it was almost impossible to reposition the Price meter in exactly the same position as the electromagnetic meter, the agreement was fair with Price meter readings ranging from 92 to 117 percent of the electromagnetic velocity meter readings.

3 Analysis of Data

The maximum local water-surface slope over a distance of 100 ft at all impingement sites ranged from 18 to 82 ft/mile with an average of 45 ft/mile or about 2.4 times the overall stream gradient.

Most sites had maximum point velocities exceeding 14 ft/sec. Maximum depth-averaged velocity exceeded 12 ft/sec at many sites, and similar to sharp bendways, depth-averaged velocity remained high over a significant part of the side slope. Velocity profiles were skewed so that the maximum point velocity over the toe of slope often occurred at 0.4-0.6 depth above the bottom. This type of velocity profile is typical of sharp bendways and would place a much greater stress on a revetment than a typical profile having the maximum point velocity closer to the water surface.

Part of the objective of this study was to develop methods for estimating impinged flow velocities in braided channels. One of the techniques used in meandering channels is to relate the maximum velocity in a bend to the average channel velocity at the bend entrance. In sharply curved bends the ratio of maximum side slope velocity V_{ss} to average channel velocity generally ranges up to 1.6. V_{ss} in the riprap design procedure given in Engineer Manual (EM) 1110-2-1601[1] is the depth-averaged velocity at 20 percent up the slope from the toe. Impingement sites are simply poorly aligned bendways. Defining the average channel velocity in a braided channel approaching the impingement point is difficult compared to single channels. One option would be to use the average channel velocity from an HEC-2 water-surface profile computation for a discharge of 15,000 cfs. Water-surface profiles were previously computed by the Walla Walla District for a discharge of about 25,000 cfs. At this discharge, the midchannel bars are submerged and flow is generally parallel to the levees. At a discharge of 15,000 cfs, flow is confined to the single or multiple braided channels that are not parallel to the levees. To use HEC-2 for flow within the braided channels would require cross-section data far beyond what was used for the 25,000-cfs discharge. A method is needed for determining the average channel velocity for intermediate flows.

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[1] Headquarters, U.S. Army Corps of Engineers. (1991 (1 July)). "Hydraulic design of flood control channels," EM 1110-2-1601, U.S. Government Printing Office, Washington, DC.

One possibility is to use the observed cross sections in HEC-2 to determine the cross-sectional area when the stage is near the top of the midchannel bars, which was the stage when the field measurements were conducted. This area was selected because the most severe impingement is generally assumed to occur when the discharge produces a stage near the top of the midchannel bars. The Committee on Channel Stabilization[1] states that "revetment size should be based on bank velocities corresponding to design water surface with consideration being given to the fact that direct impingement of moderate flows (15,000 cfs) may cause local damage more severe than the design flows." Plates 49-52 show eight cross sections downstream of the Gros Ventre River along with a stage near the tops of the midchannel bars. Unfortunately only one of the HEC-2 cross sections occurred near the velocity sites reported herein. Measurements at site B-4 coincided with the cross section at sta 7+05. The average channel area below the stages observed during June 1991 was about 2,000 sq ft. Since the stage was close to the tops of the midchannel bars, the measurements reported herein were close to the maximum in terms of levee attack and velocity magnitude. Using a discharge of 15,000 cfs for the reach downstream of the Gros Ventre River and an average channel area of 2,000 sq ft resulted in an average channel velocity of 7.5 ft/sec. The maximum depth-averaged velocity measured near the toe of the riprap revetment was about 11.9 ft/sec, giving a ratio of maximum depth-averaged velocity to average channel velocity of about 1.6, which is reasonable based on results from meandering channels. More data are needed to test this approach. Additional data are needed at discharges both less than and greater than the discharges measured herein to test the hypothesis that the impingement is most severe when the stage is near the tops of the midchannel bars.

Another objective of this study was to develop techniques for estimating local scour at impingement points. The lack of bed material data prevents the development of any general guidance, but information specific to the Snake River can be developed from the observed data. Plate 53 shows the tops of the main channel bars and the deepest point in the cross section, both taken from survey data collected in 1988. The detailed channel data suggest that the data were taken during low-flow conditions. The difference between the two lines ranges from 4 to 14 ft. The velocity plots presented herein show a maximum depth below the 15,000-cfs water level of about 15 ft. If the 15,000-cfs flow rate is near the conditions of maximum levee attack, then the design scour for the Snake River reach shown in Figure 1 should be a minimum of 17 ft below the elevation of the midchannel bars as defined in Plate 53. This allows a 2-ft margin below the deepest observed scour.

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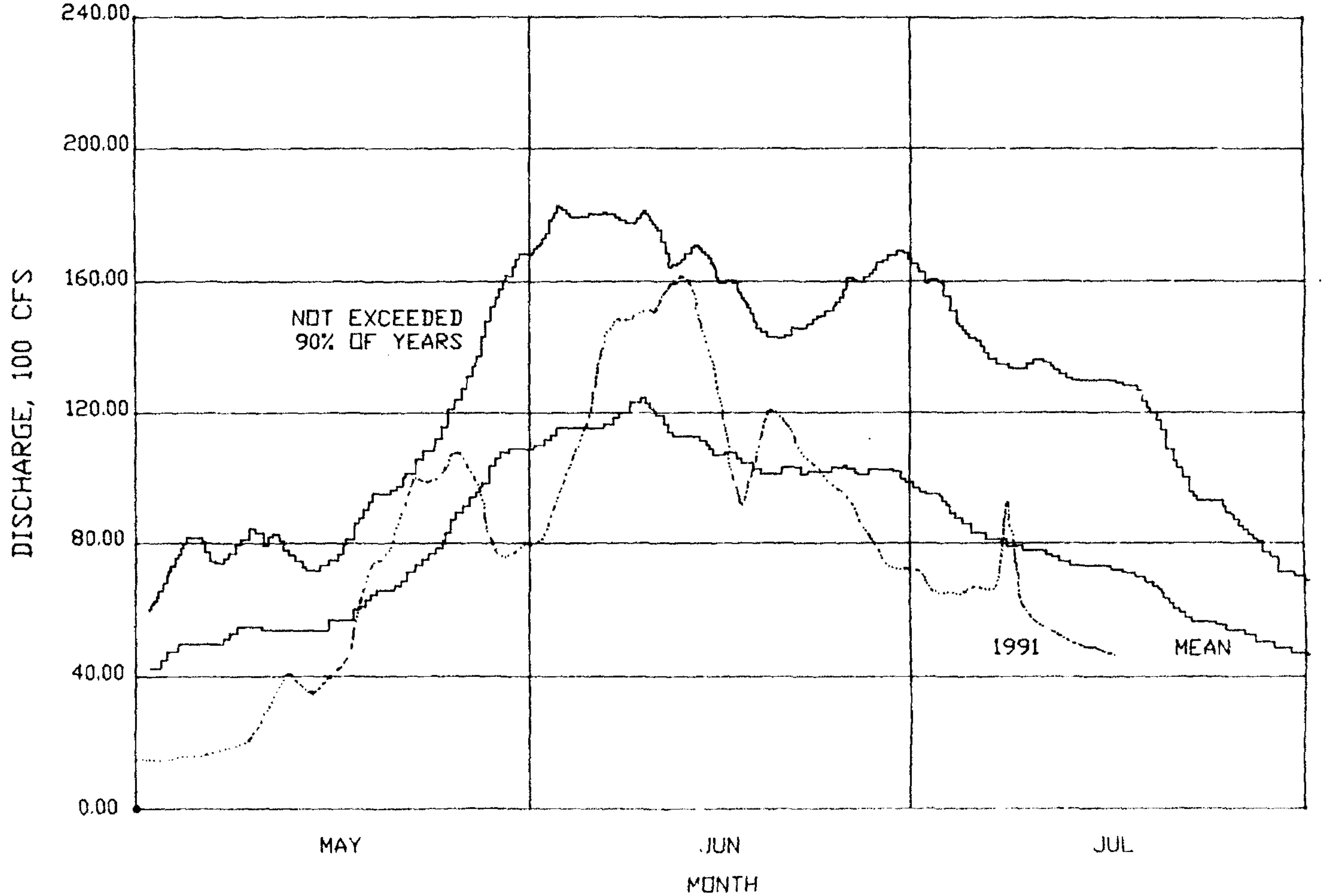
[1] Committee on Channel Stabilization, Corps of Engineers, U.S. Army. (1974). "Jackson Hole, Wyoming, flood control project," Technical Report No. 11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

4 Summary and Conclusions

Flow impingement on the Snake River results in depth-averaged velocity exceeding 12 ft/sec near the revetted levees. Maximum point velocities were up to 16 ft/sec. Typical impingement points had flow approaching the levee at angles up to 70 deg. Water-surface slopes at the impingement sites average 2.4 times the average slope of the stream.

A method for estimating impingement velocities is proposed herein based on average channel velocity with a flow producing a stage near the tops of the midchannel bars. This average velocity should be multiplied by 1.6 to obtain maximum impingement velocities. Additional data are needed on other impingement streams as well as data to test the hypothesis that stages near the top of the midchannel bars produce the most severe levee attack.

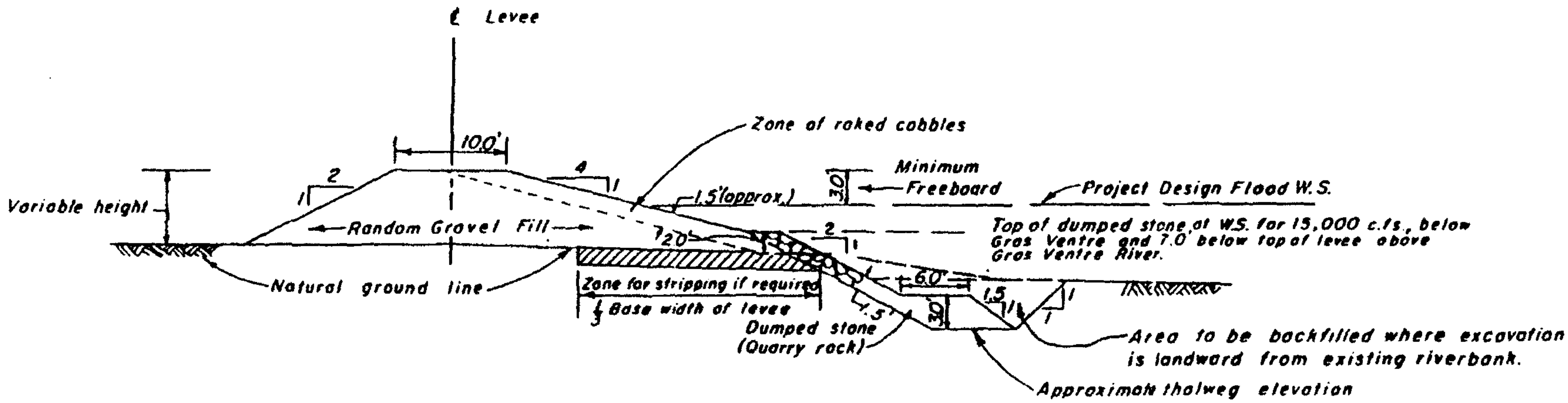
General guidance on scour depths could not be developed from these data because of the lack of bed material data. Results from these measurements and previous cross sections obtained in 1988 suggest that if the intermediate flows reported herein produce the most severe levee attack, design scour depths should be a minimum of 17 ft below the tops of the midchannel bars.



GAGE LOCATION AT BELOW FLAT CREEK

MEAN DAILY DISCHARGE

Plate 1



TYPICAL LEVEE SECTION

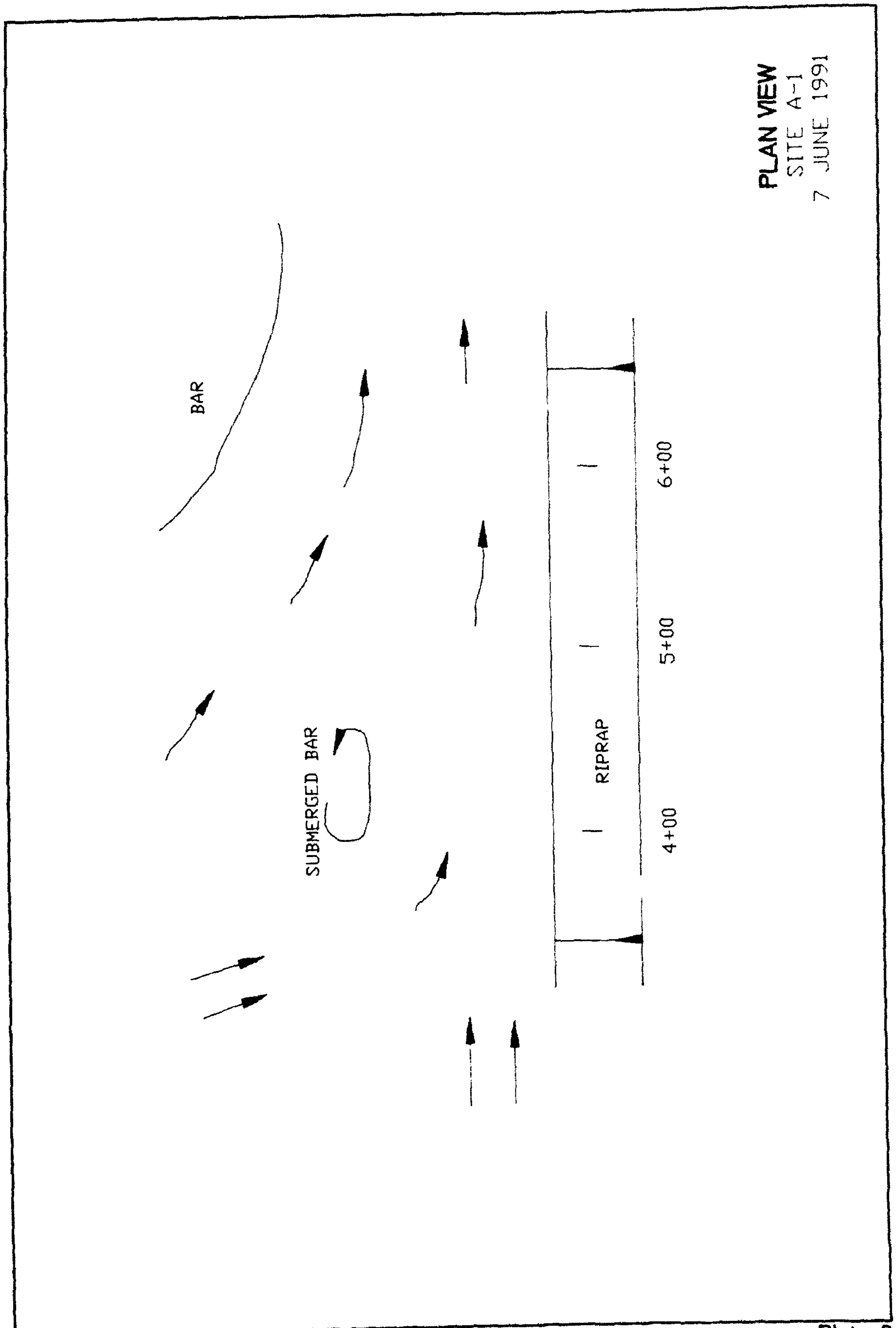

PLAN VIEW
SITE A-1
7 JUNE 1991
BAR
SUBMERGED BAR
RIPRAP
4+00
5+00
6+00

Plate 3

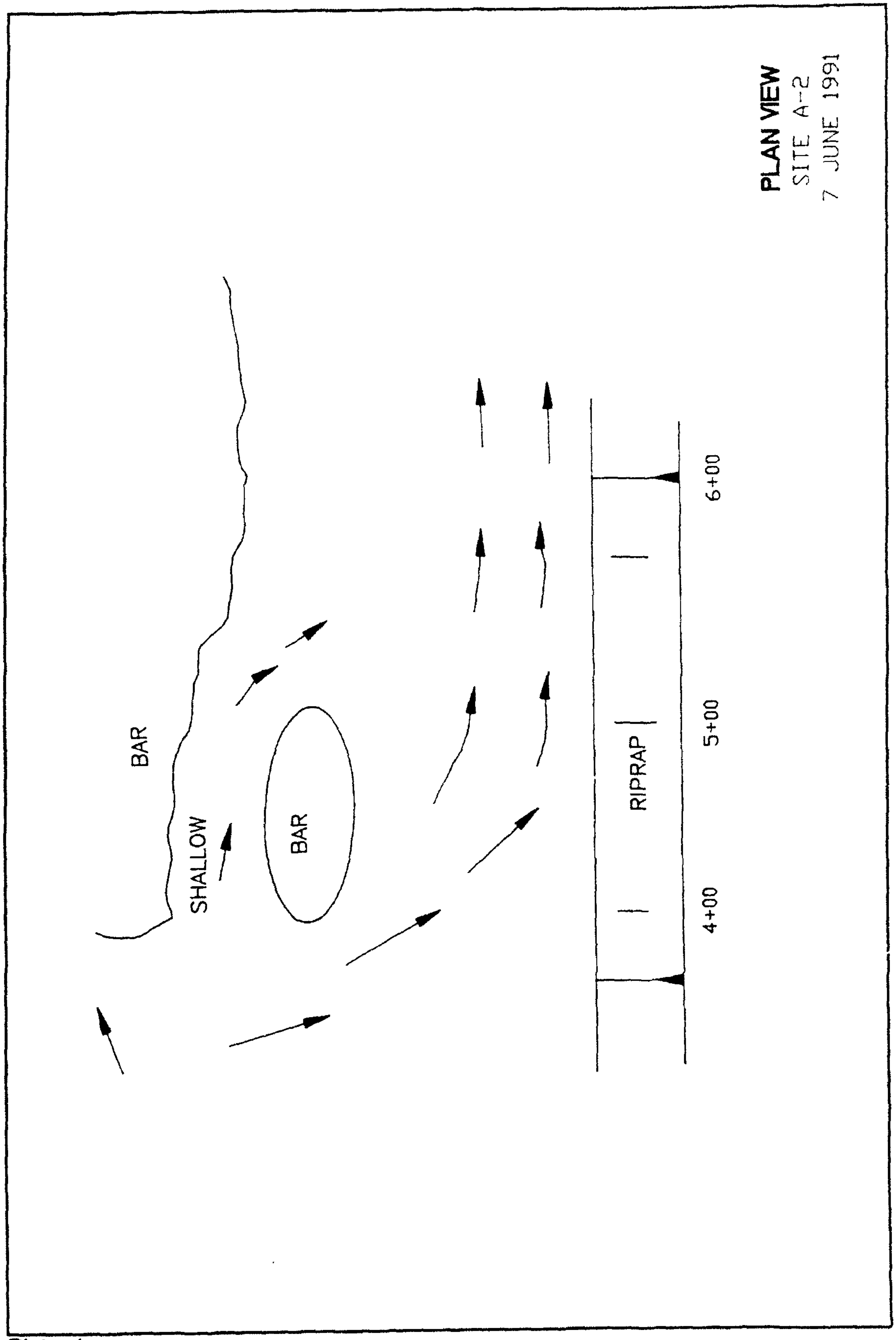
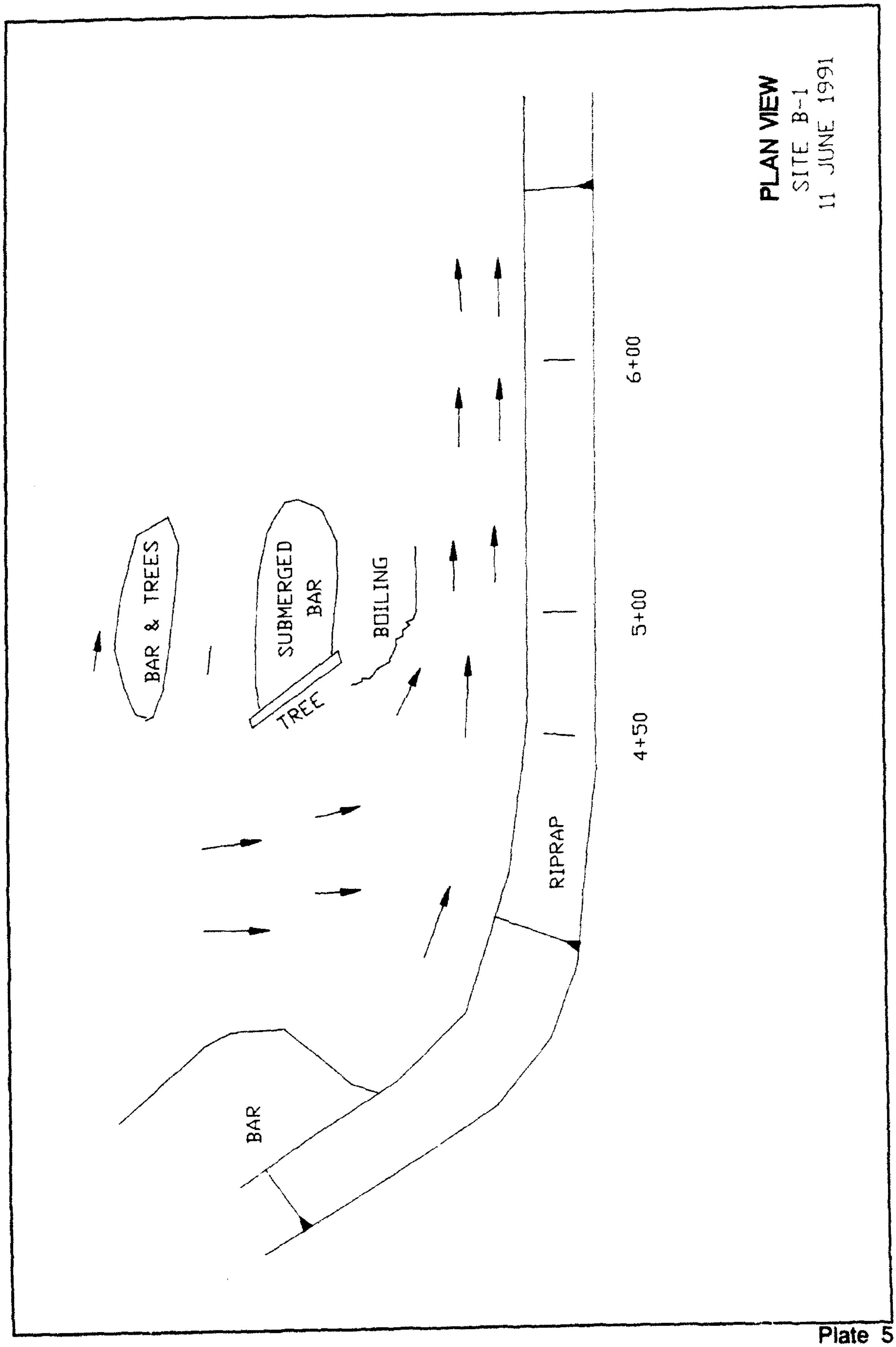
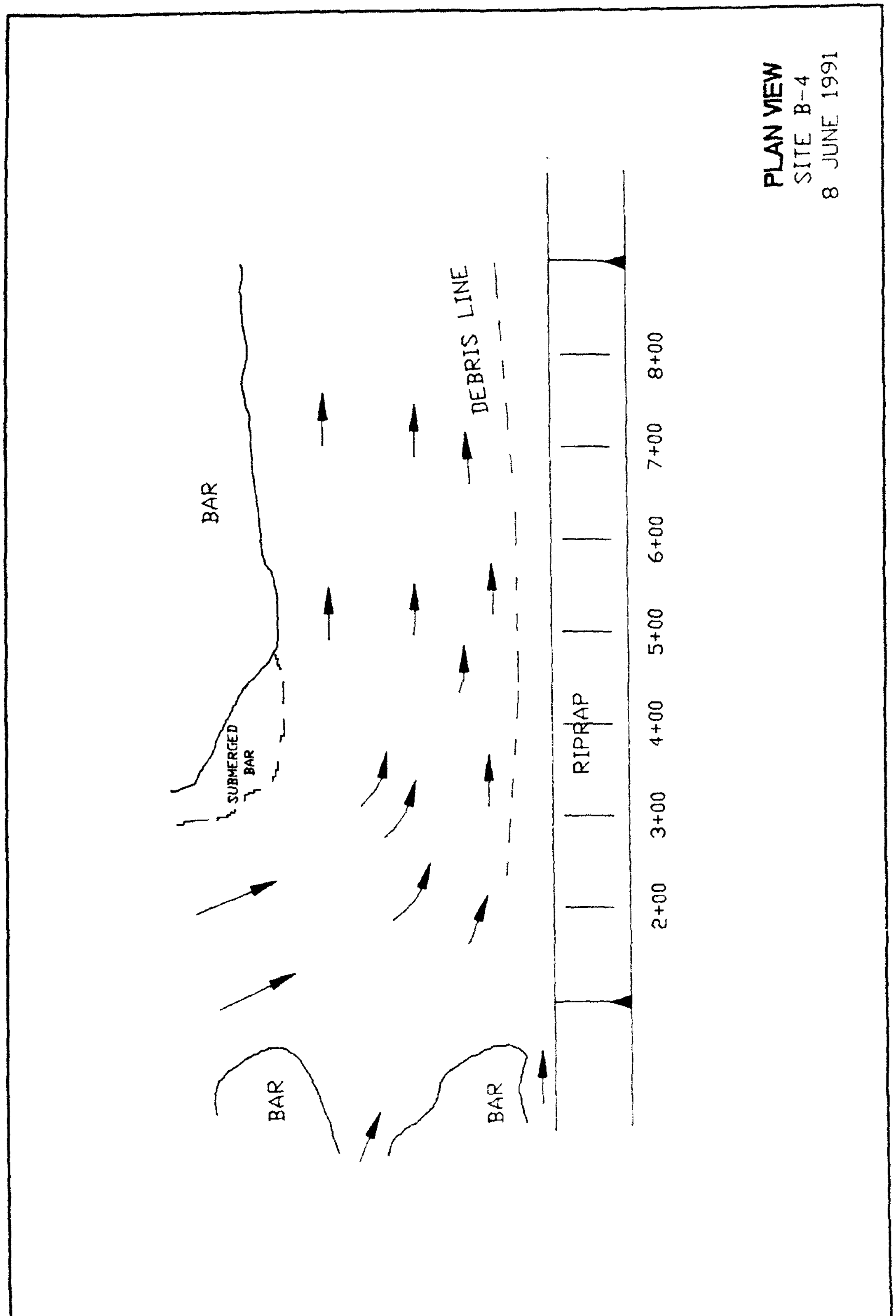

PLAN VIEW
SITE A-2
7 JUNE 1991
BAR
SHALLOW
BAR
RIPRAP
4+00
5+00
6+00

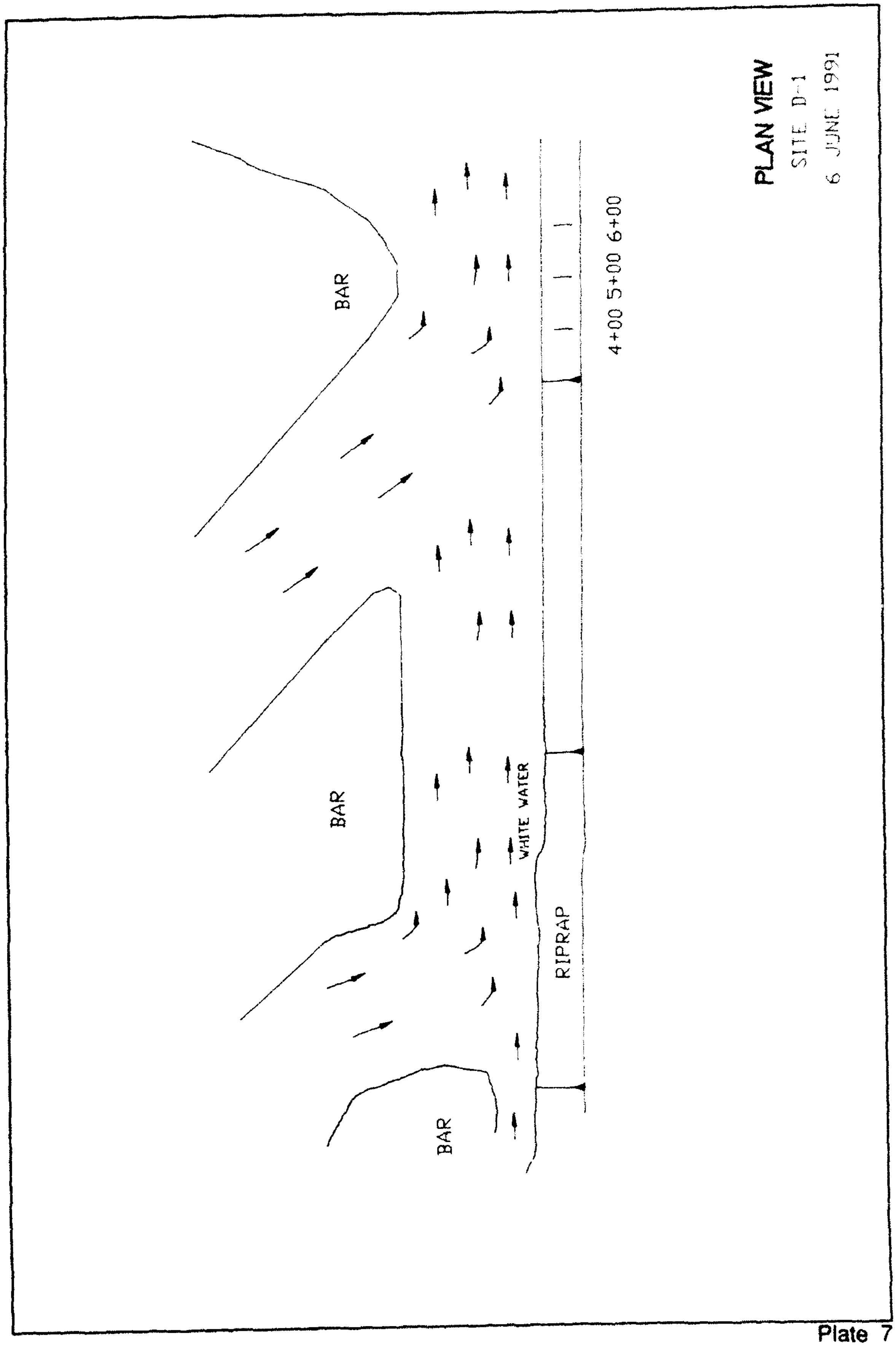
Plate 4


PLAN VIEW
SITE B-1
11 JUNE 1991
6+00
5+00
4+50
BAR & TREES
SUBMERGED BAR
BOILING
TREE
RIPRAP
BAR



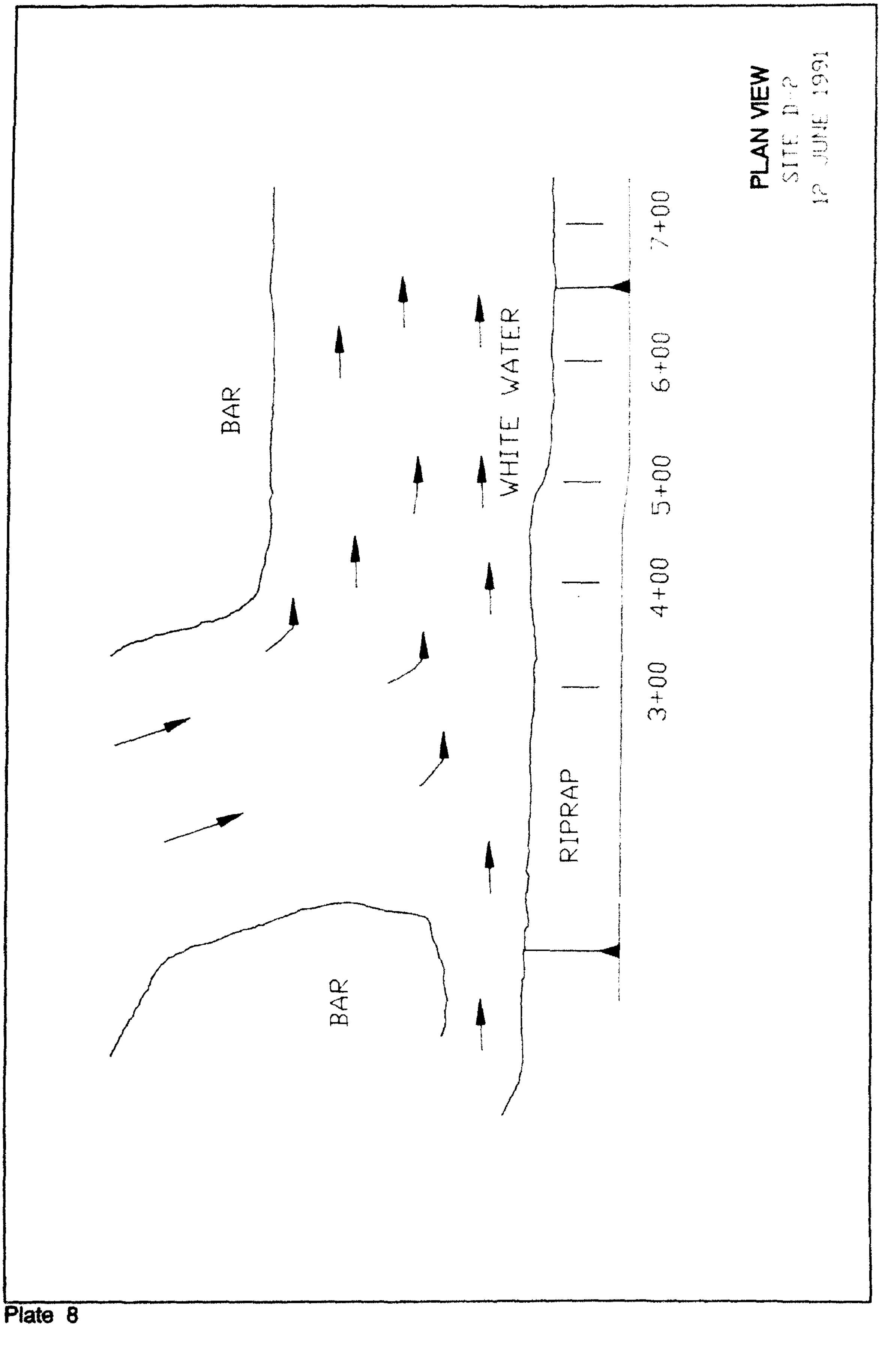
PLAN VIEW
SITE B-4
8 JUNE 1991
BAR
SUBMERGED BAR
DEBRIS LINE
RIPRAP
BAR
BAR
2+00
3+00
4+00
5+00
6+00
7+00
8+00

Plate 6



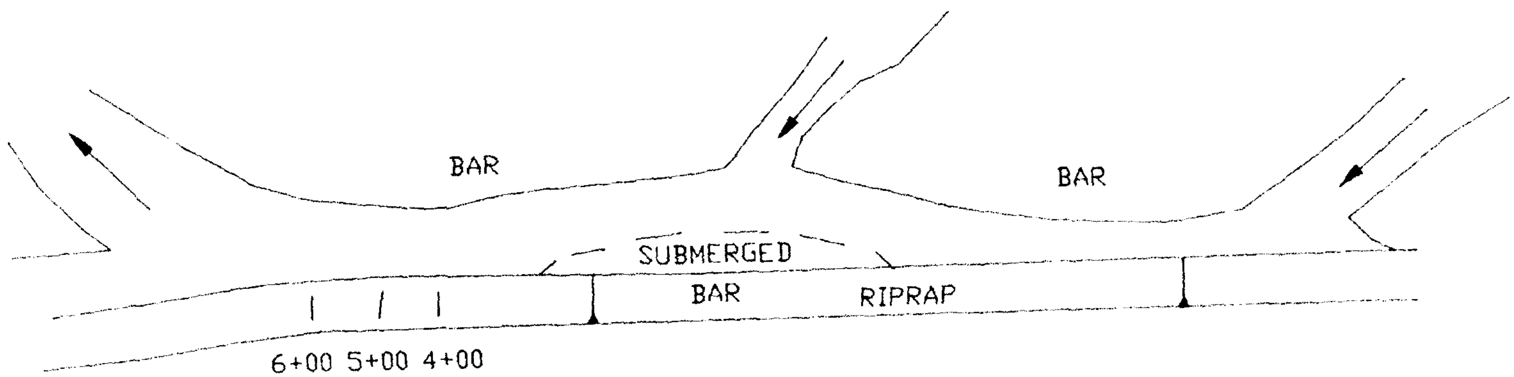
PLAN VIEW
SITE D-1
6 JUNE 1991
4+00 5+00 6+00
BAR
BAR
BAR
WHITE WATER
RIPRAP

Plate 7



PLAN VIEW
SITE D-2
12 JUNE 1991
BAR
WHITE WATER
BAR
RIPRAP
7+00
6+00
5+00
4+00
3+00

Plate 8



PLAN VIEW

SITE E-1
6 JUNE 1991

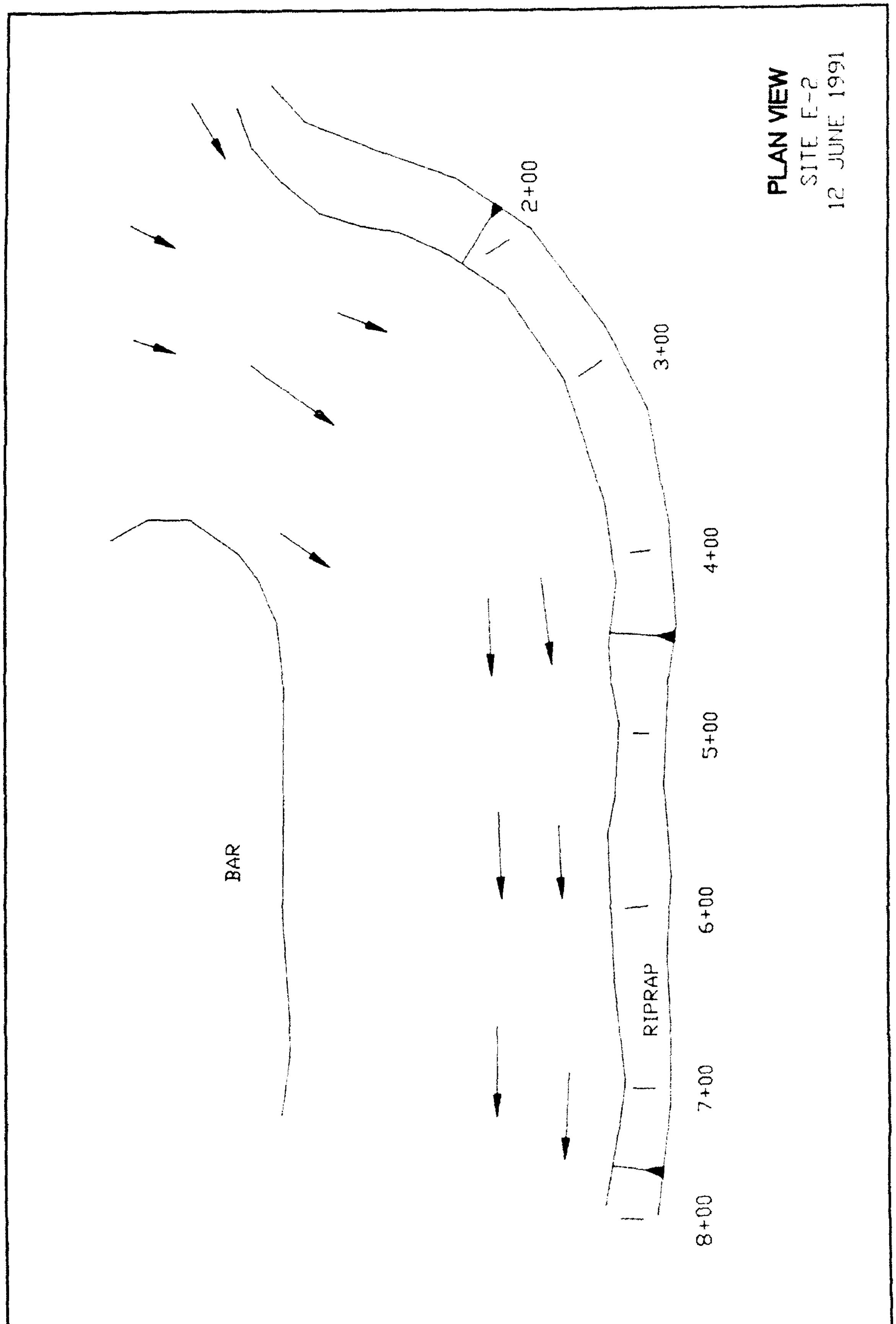
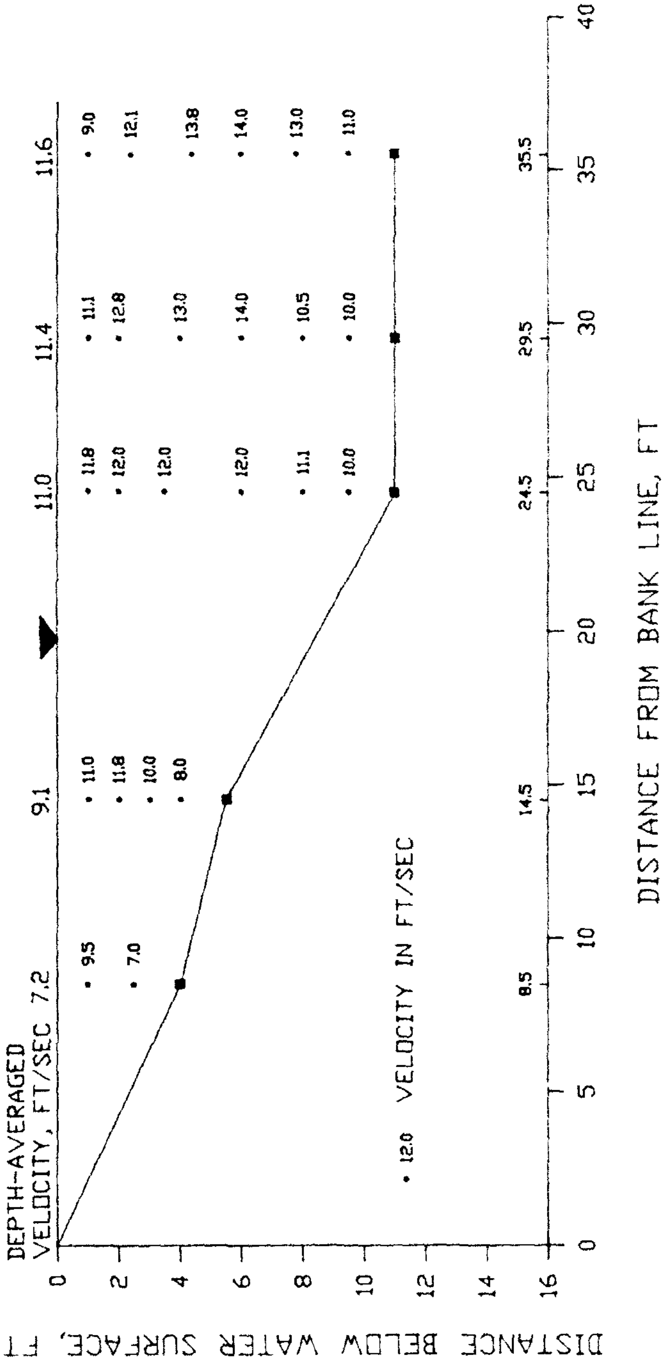
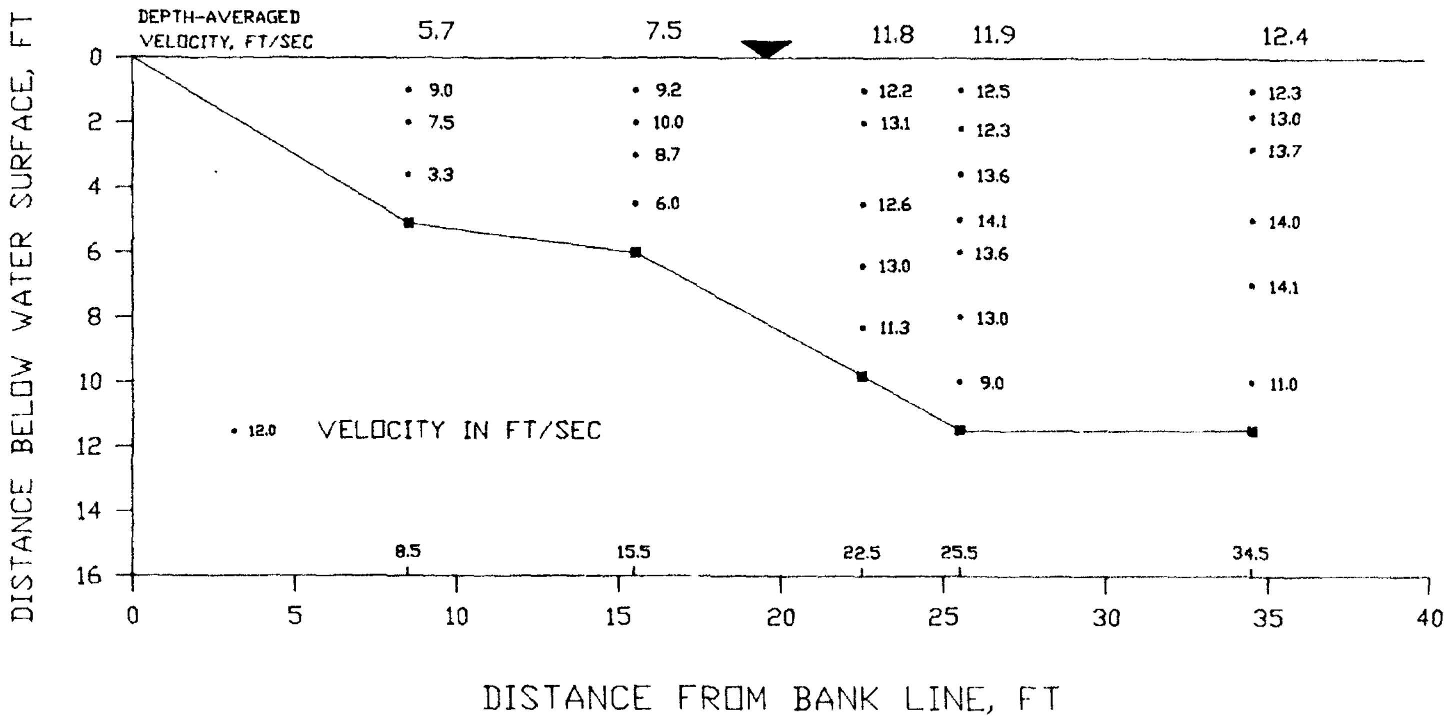

PLAN VIEW
SITE E-2
12 JUNE 1991
2+00
3+00
4+00
5+00
6+00
7+00
8+00
BAR
RIPRAP

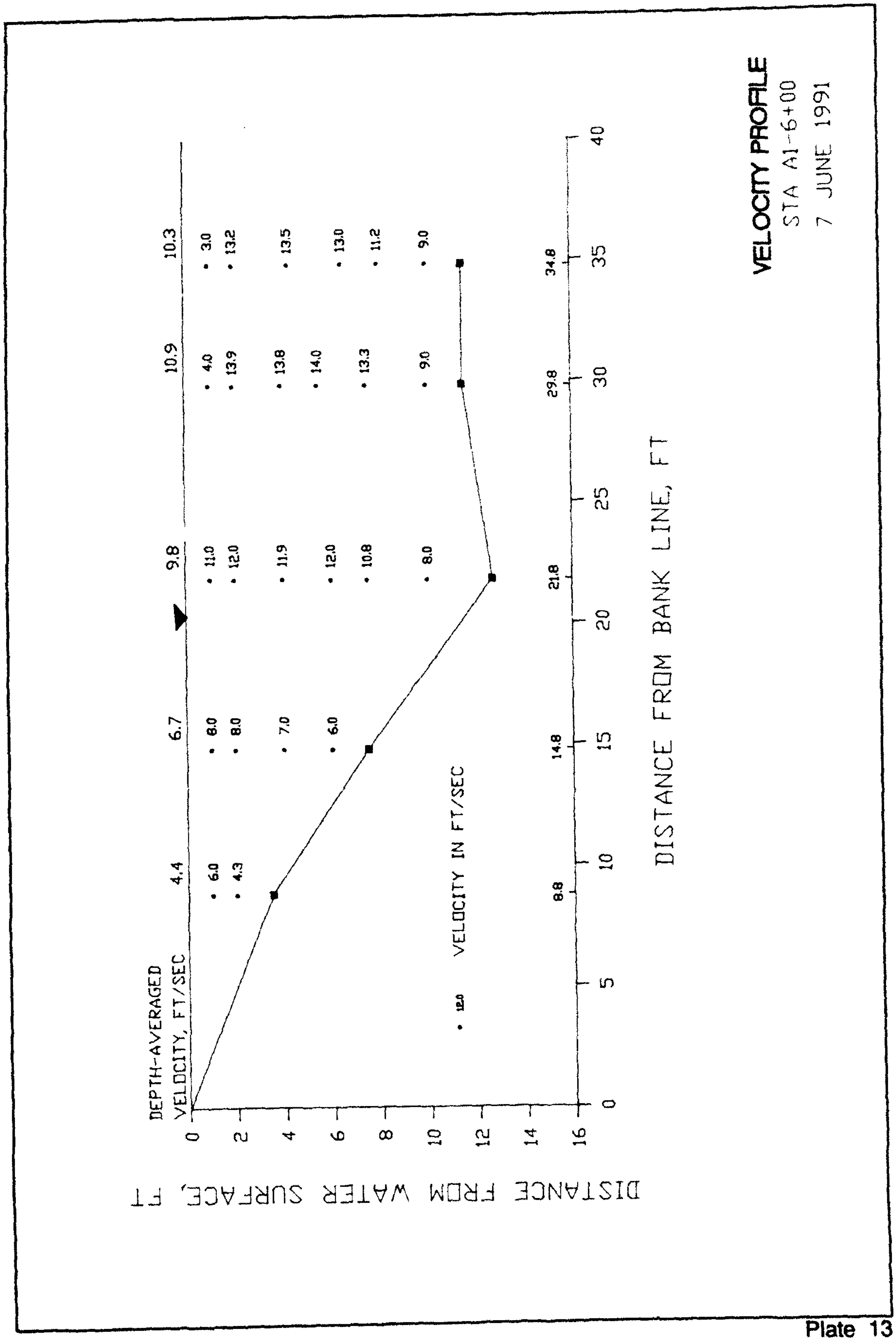
Plate 10

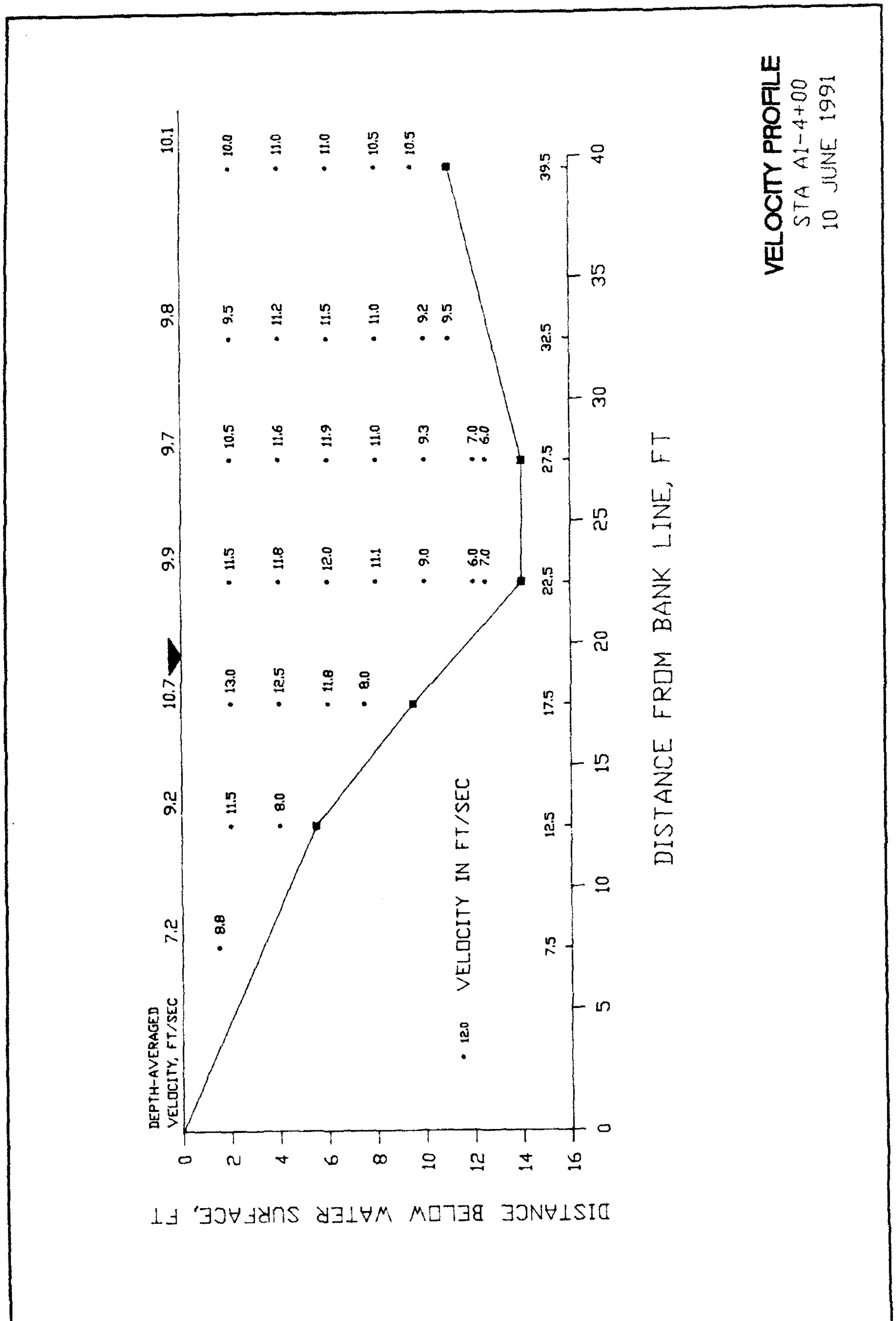


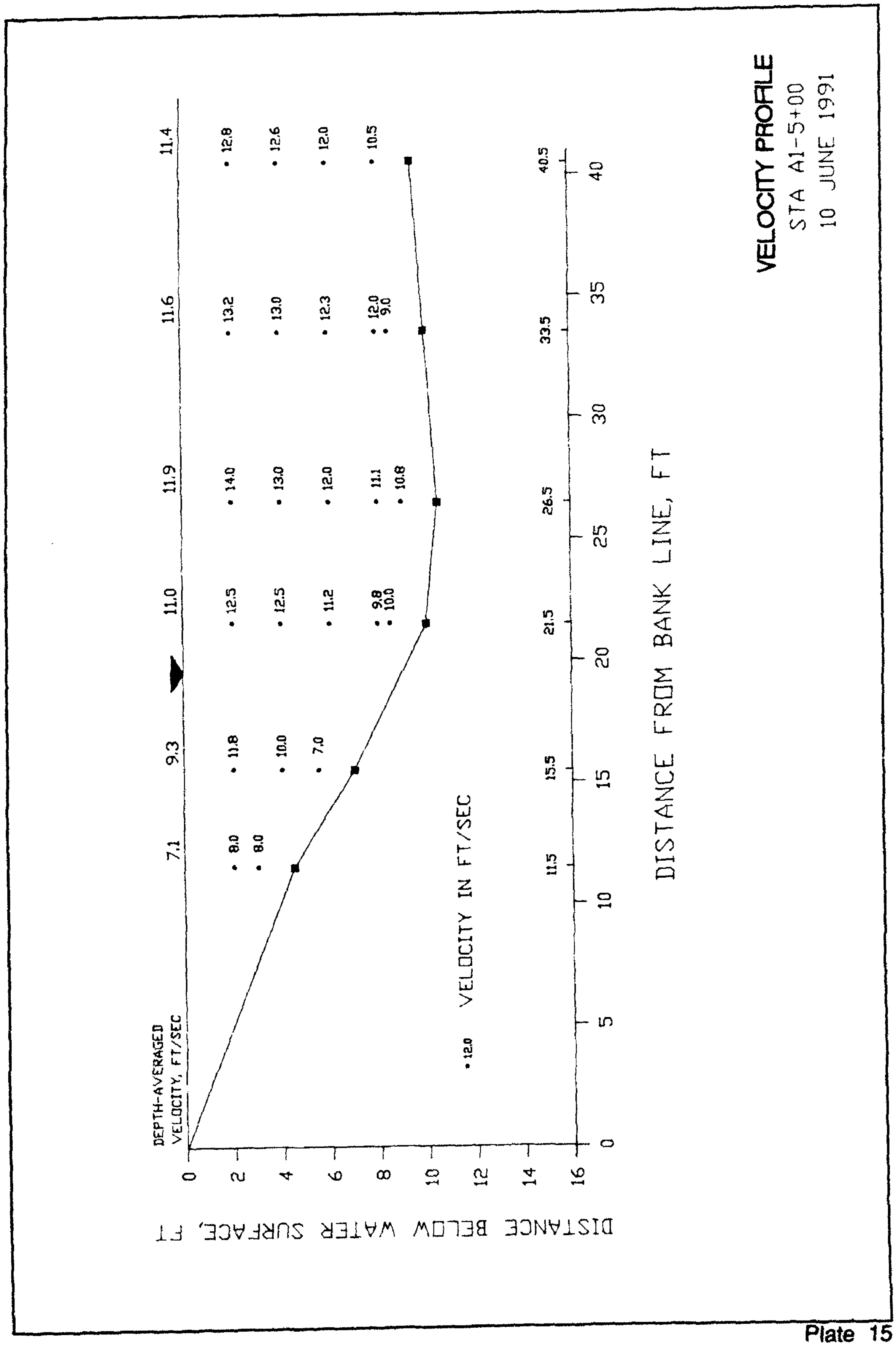
VELOCITY PROFILE
STA A1-4+00
7 JUNE 1991



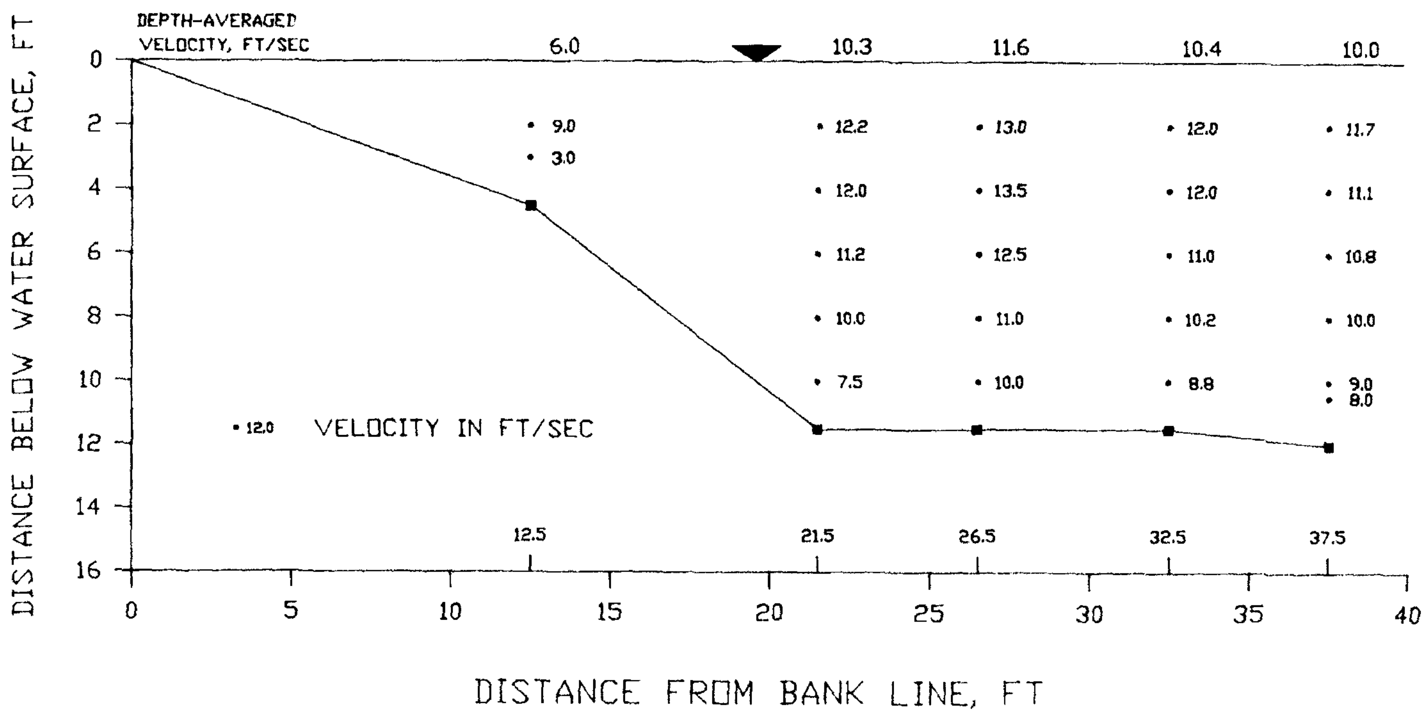
VELOCITY PROFILE
STA A1-5+00
7 JUNE 1991


VELOCITY PROFILE
STA A1-6+00
7 JUNE 1991
DEPTH-AVERAGED VELOCITY, FT/SEC
4.4
6.7
9.8
10.9
10.3
VELOCITY IN FT/SEC
DISTANCE FROM BANK LINE, FT
DISTANCE FROM WATER SURFACE, FT
8.8
14.8
21.8
29.8
34.8

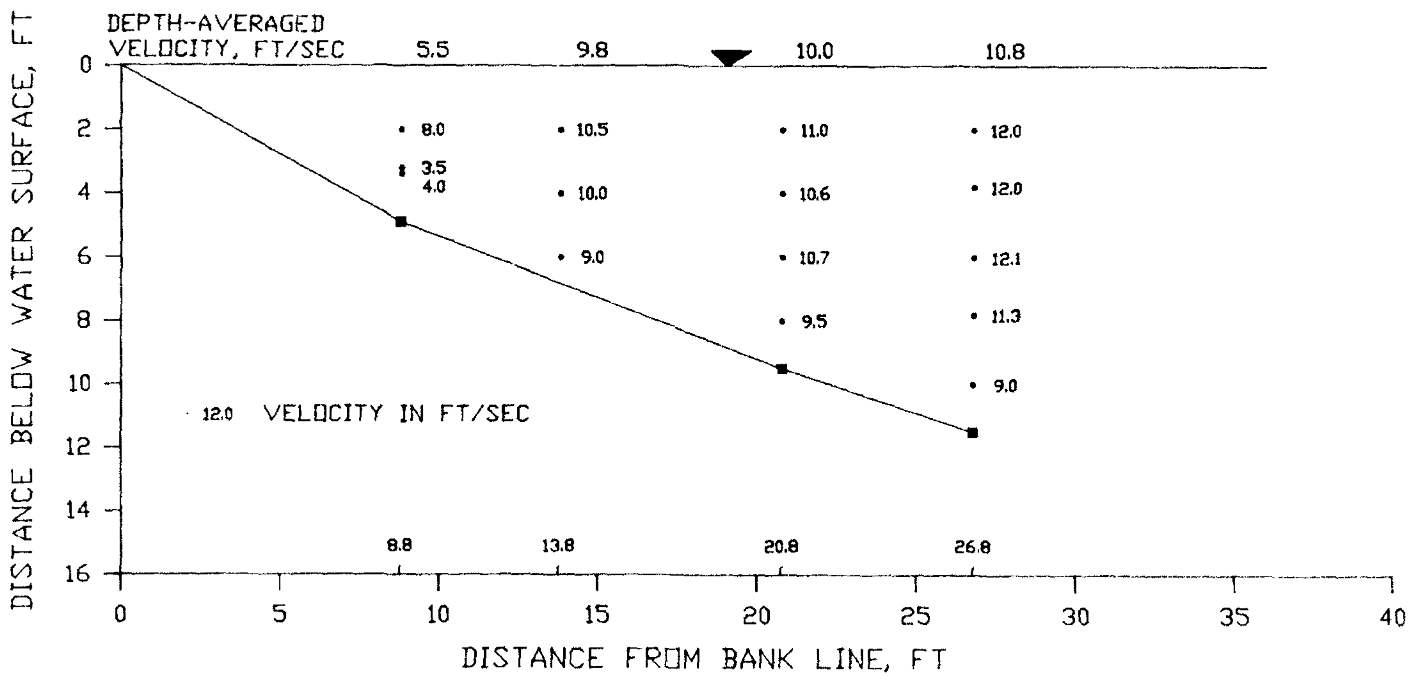

VELOCITY PROFILE
STA A1-4+00
10 JUNE 1991
DISTANCE FROM BANK LINE, FT
DISTANCE BELOW WATER SURFACE, FT
DEPTH-AVERAGED VELOCITY, FT/SEC
VELOCITY IN FT/SEC
7.2
9.2
10.7
9.9
9.7
9.8
10.1



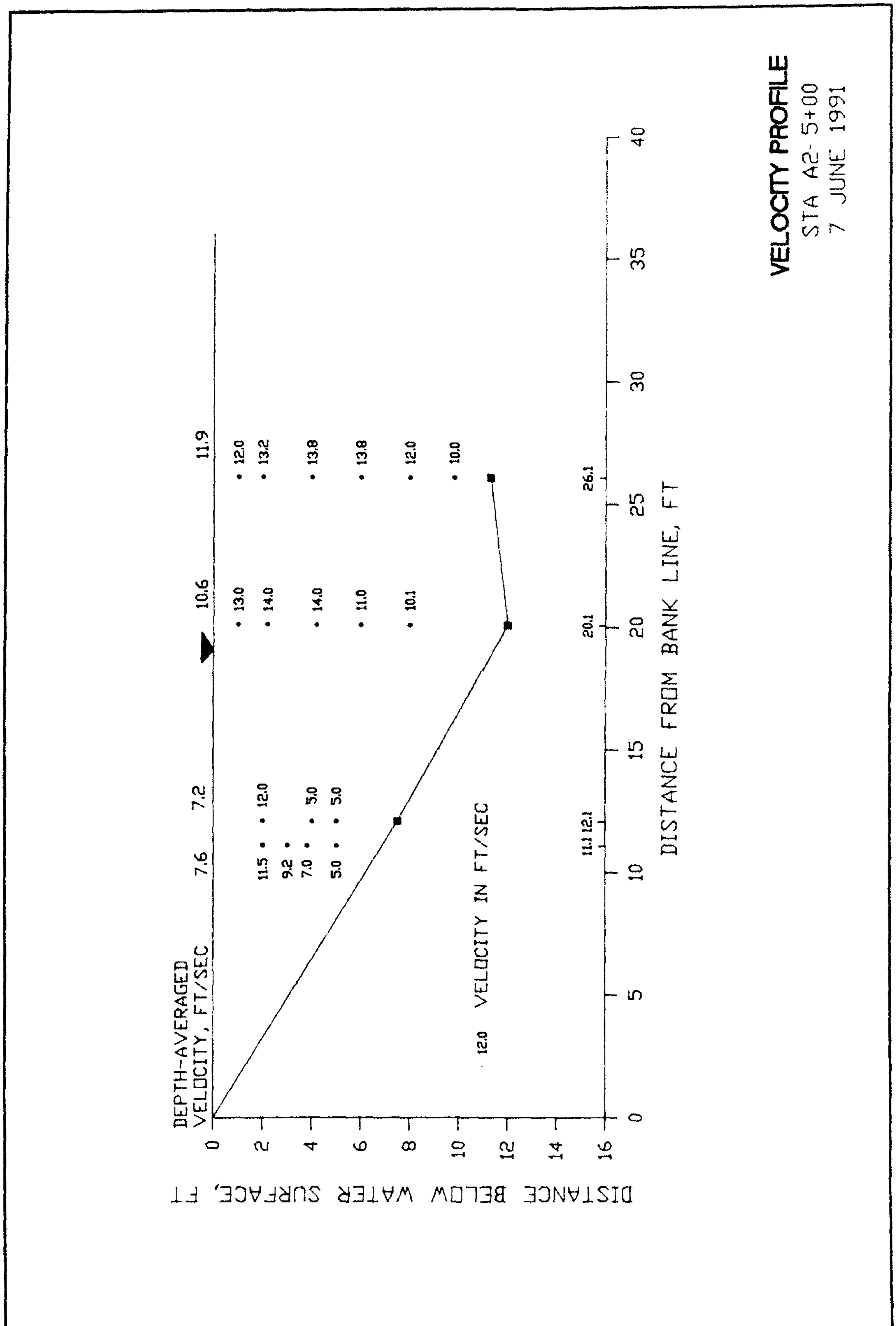
VELOCITY PROFILE
STA A1-5+00
10 JUNE 1991
DEPTH-AVERAGED
VELOCITY, FT/SEC
7.1
9.3
11.0
11.9
11.6
11.4
8.0
8.0
11.8
10.0
7.0
12.5
12.5
11.2
9.8
10.0
14.0
13.0
12.0
11.1
10.8
13.2
13.0
12.3
12.0
9.0
12.8
12.6
12.0
10.5
12.0
VELOCITY IN FT/SEC
11.5
15.5
21.5
26.5
33.5
40.5
0
5
10
15
20
25
30
35
40
DISTANCE FROM BANK LINE, FT
0
2
4
6
8
10
12
14
16
DISTANCE BELOW WATER SURFACE, FT



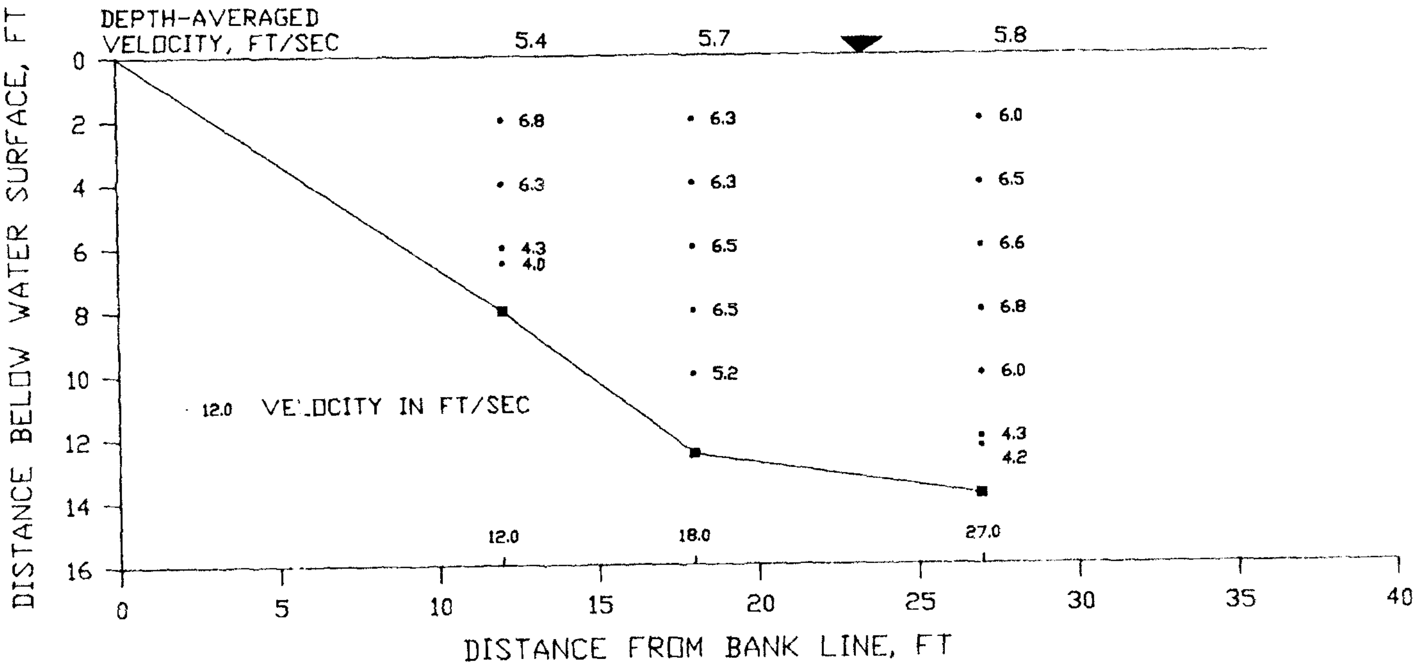
VELOCITY PROFILE
STA A1-6+00
10 JUNE 1991



VELOCITY PROFILE
STA A2-4+00
7 JUNE 1991



VELOCITY PROFILE
STA A2- 5+00
7 JUNE 1991
DEPTH-AVERAGED
VELOCITY, FT/SEC
7.6
7.2
10.6
11.9
12.0 VELOCITY IN FT/SEC
DISTANCE FROM BANK LINE, FT
DISTANCE BELOW WATER SURFACE, FT
11.1 12.1
20.1
26.1



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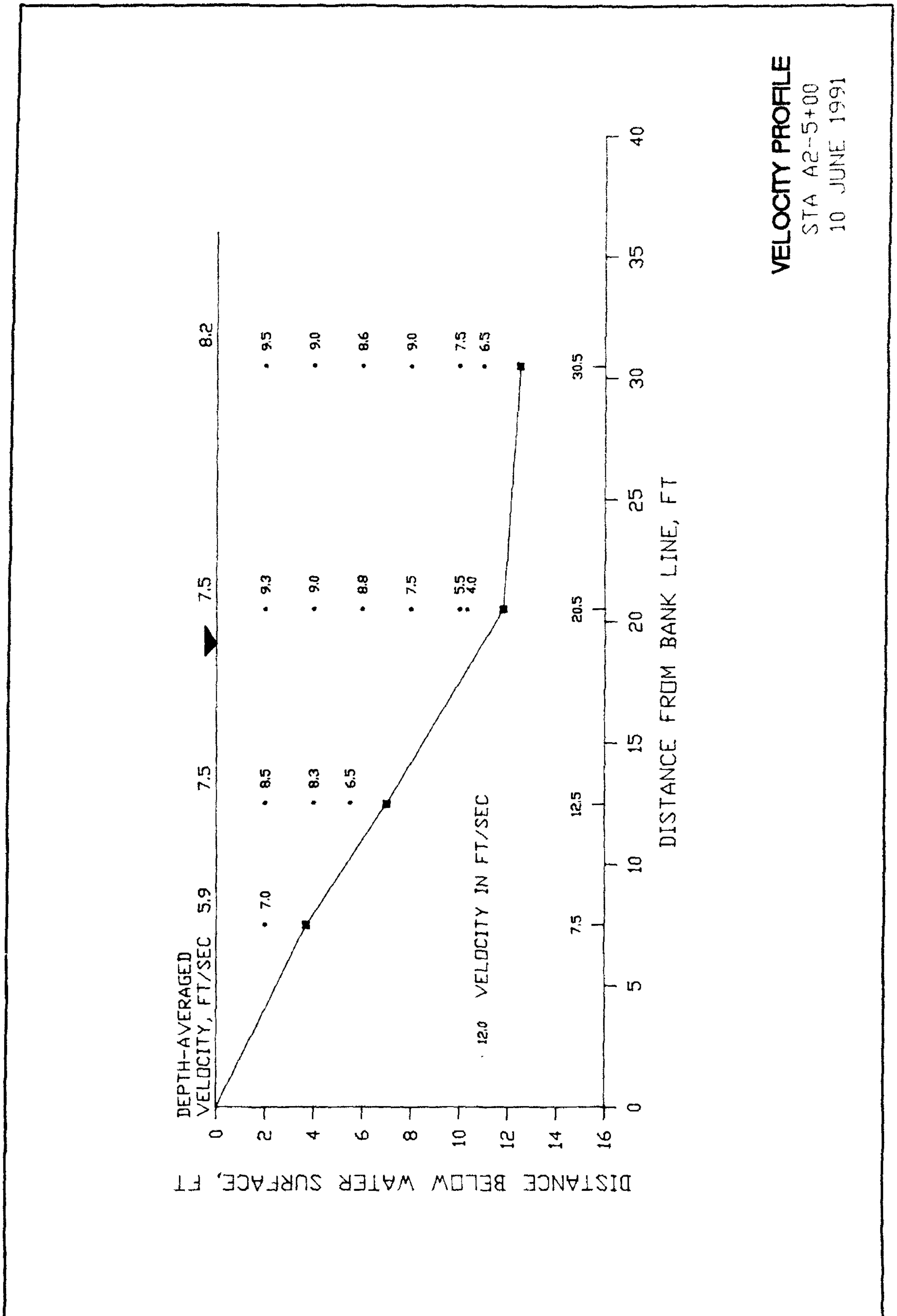
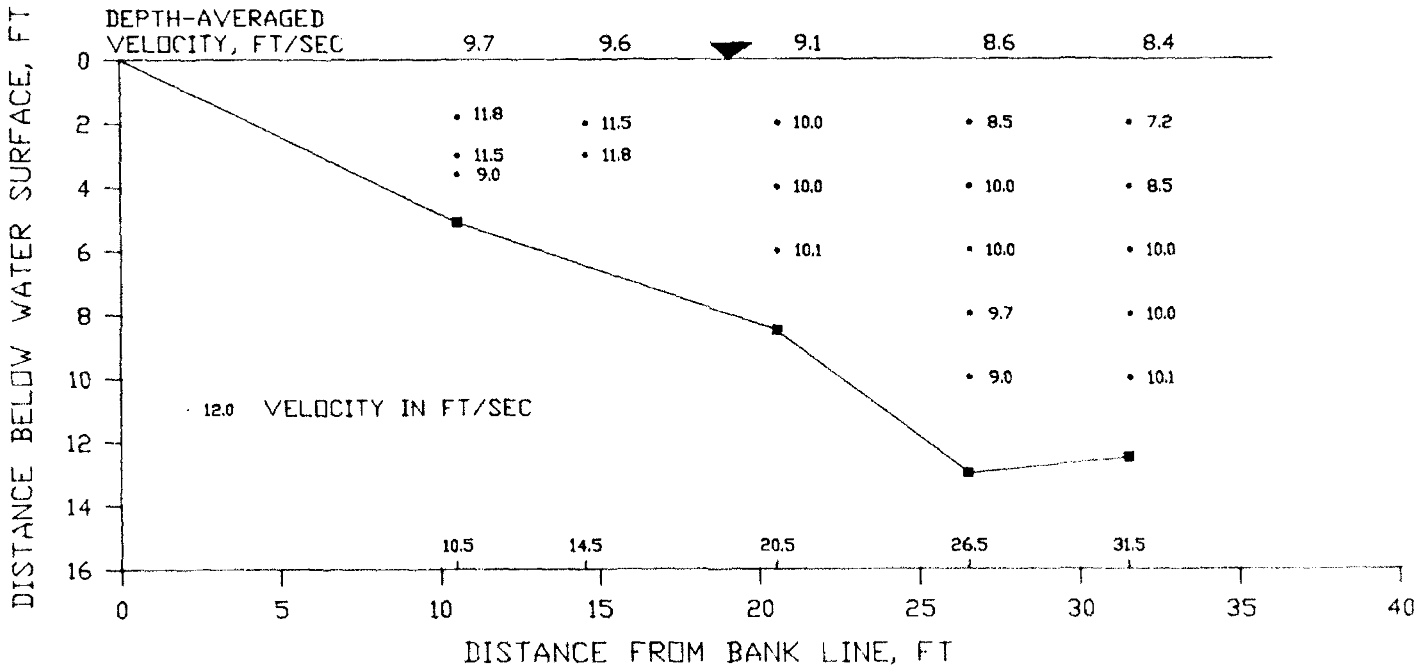
10 JUNE 1991



VELOCITY PROFILE
STA A2-5+00
10 JUNE 1991
DEPTH-AVERAGED
VELOCITY, FT/SEC
5.9
7.5
7.5
8.2
7.0
8.5
8.3
6.5
9.3
9.0
8.8
7.5
5.5
4.0
9.5
9.0
8.6
9.0
7.5
6.5
12.0
VELOCITY IN FT/SEC
7.5
12.5
20.5
30.5
0
2
4
6
8
10
12
14
16
DISTANCE BELOW WATER SURFACE, FT
0
5
10
15
20
25
30
35
40
DISTANCE FROM BANK LINE, FT

Plate 20



VELOCITY PROFILE
STA B1-4+50
8 JUNE 1991

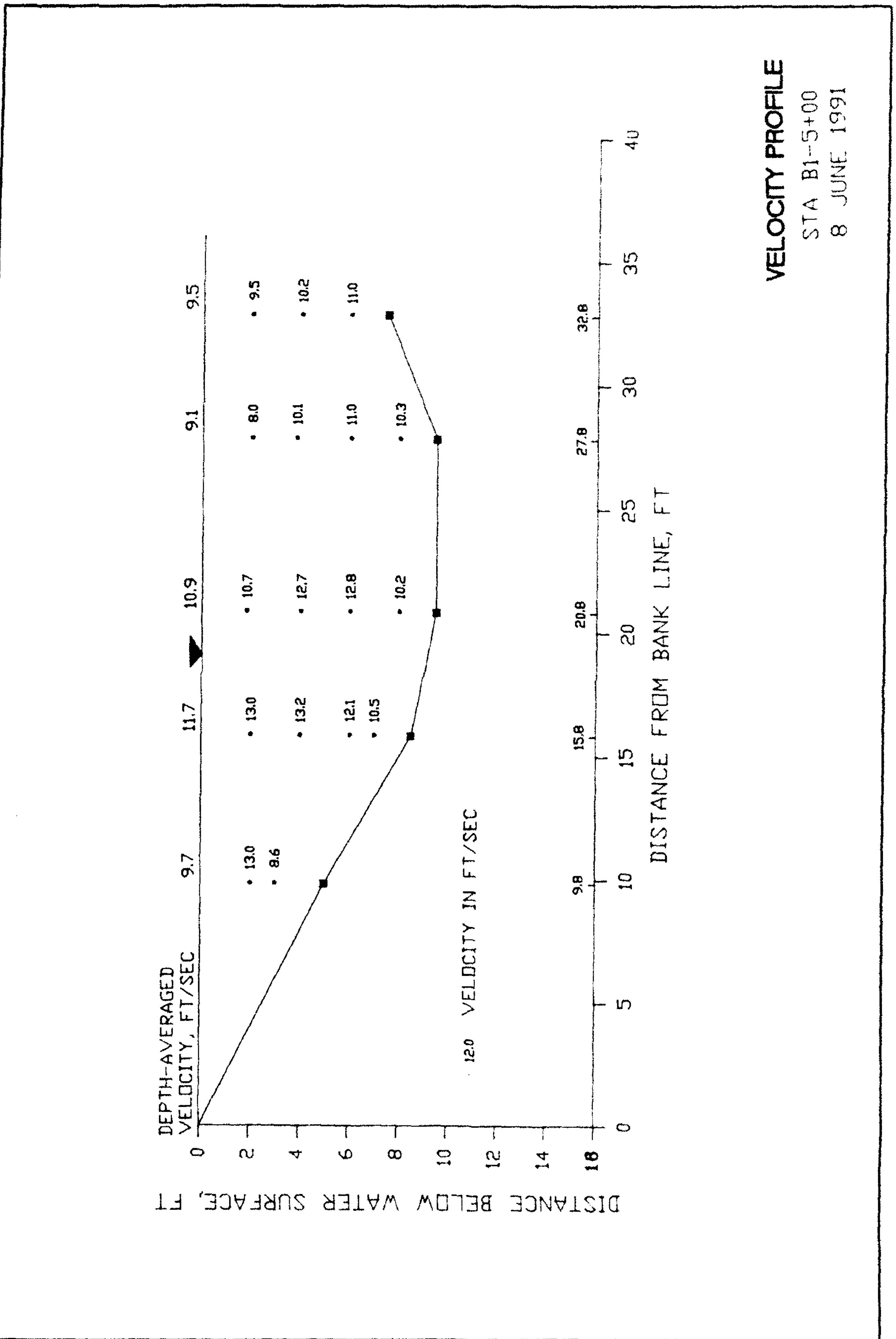
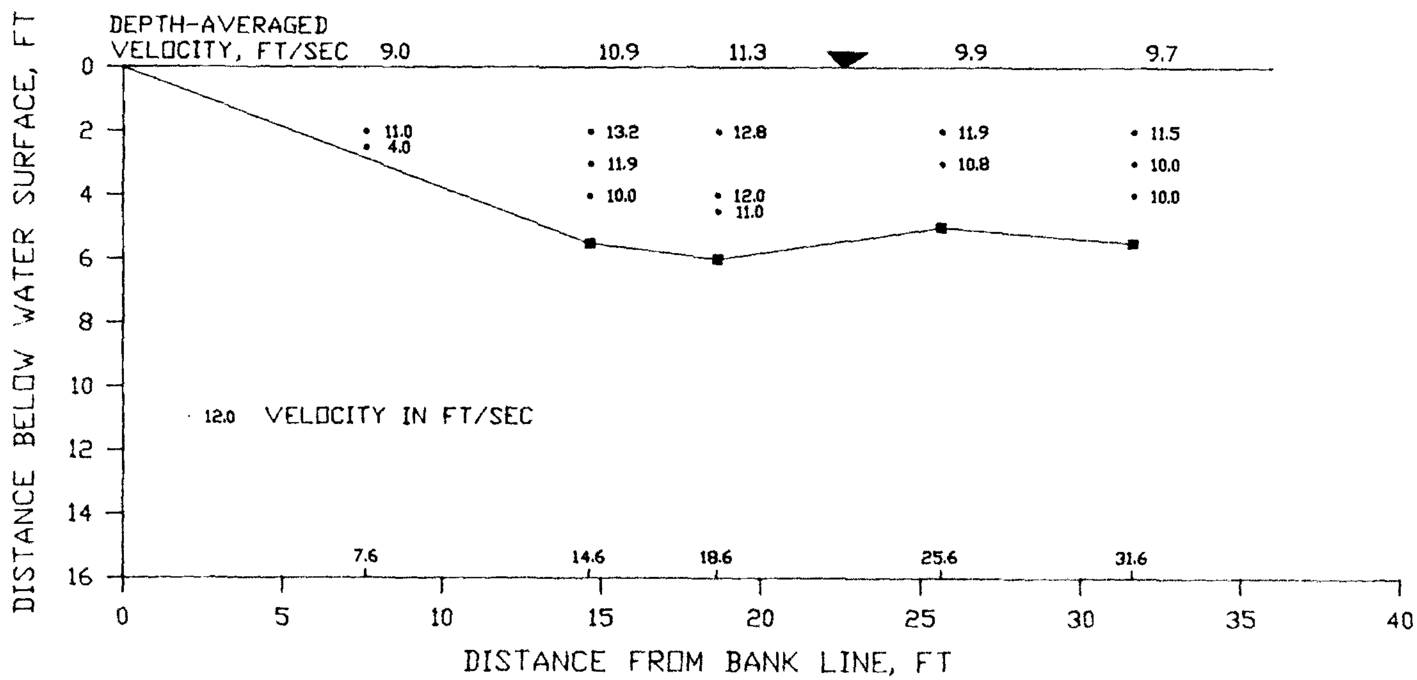

VELOCITY PROFILE
STA B1-5+00
8 JUNE 1991
DEPTH-AVERAGED VELOCITY, FT/SEC
12.0 VELOCITY IN FT/SEC
DISTANCE FROM BANK LINE, FT
DISTANCE BELOW WATER SURFACE, FT

Plate 22



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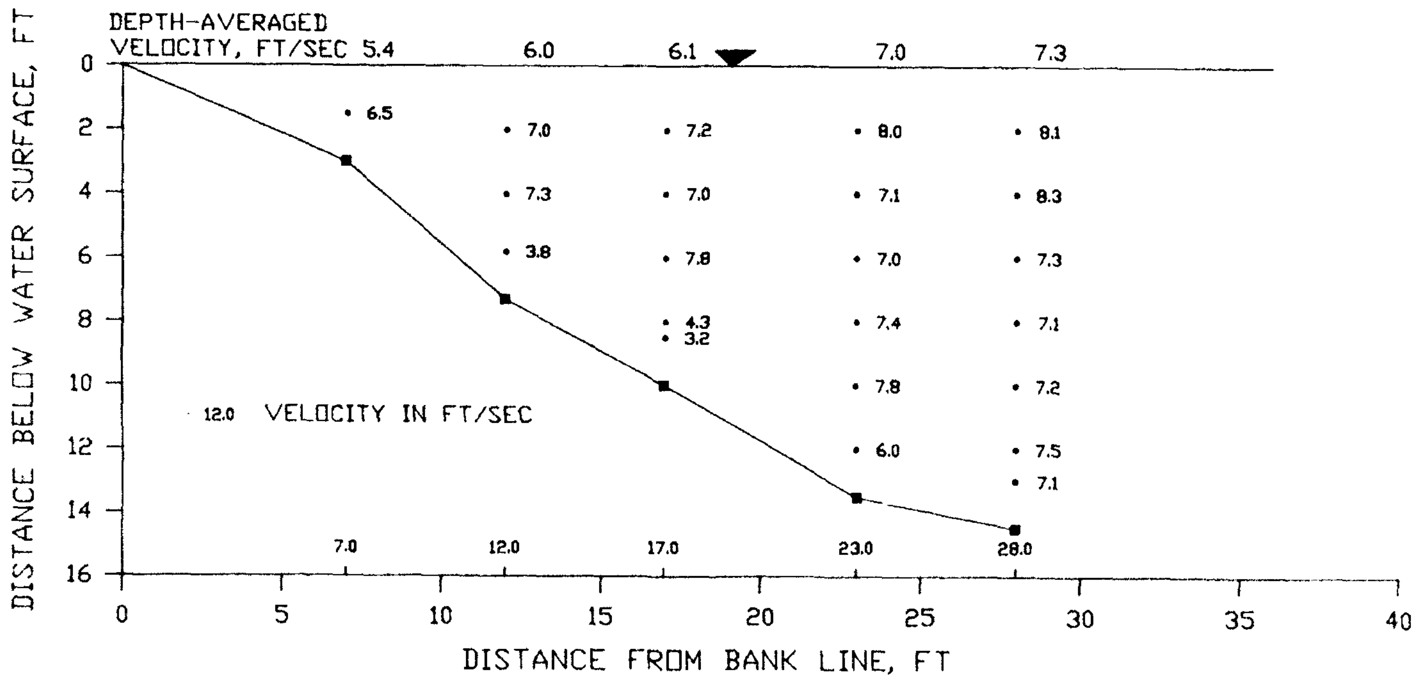
8 JUNE 1991



VELOCITY PROFILE
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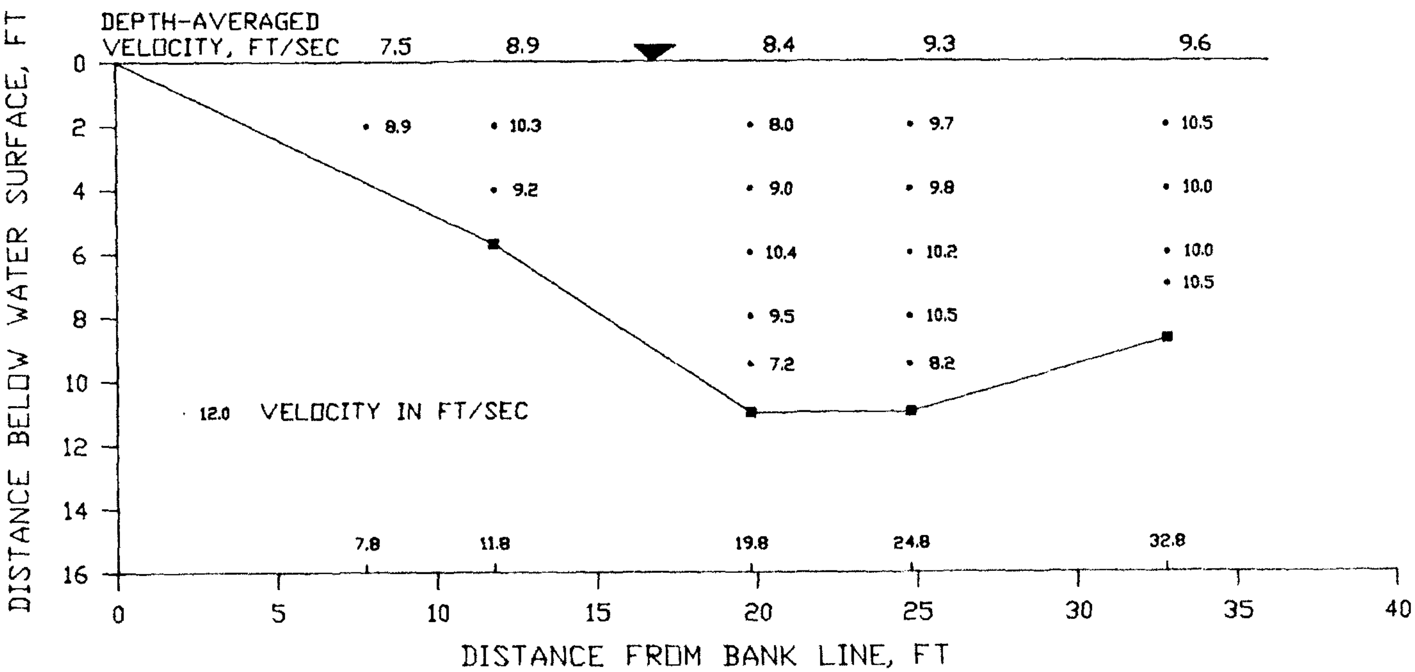
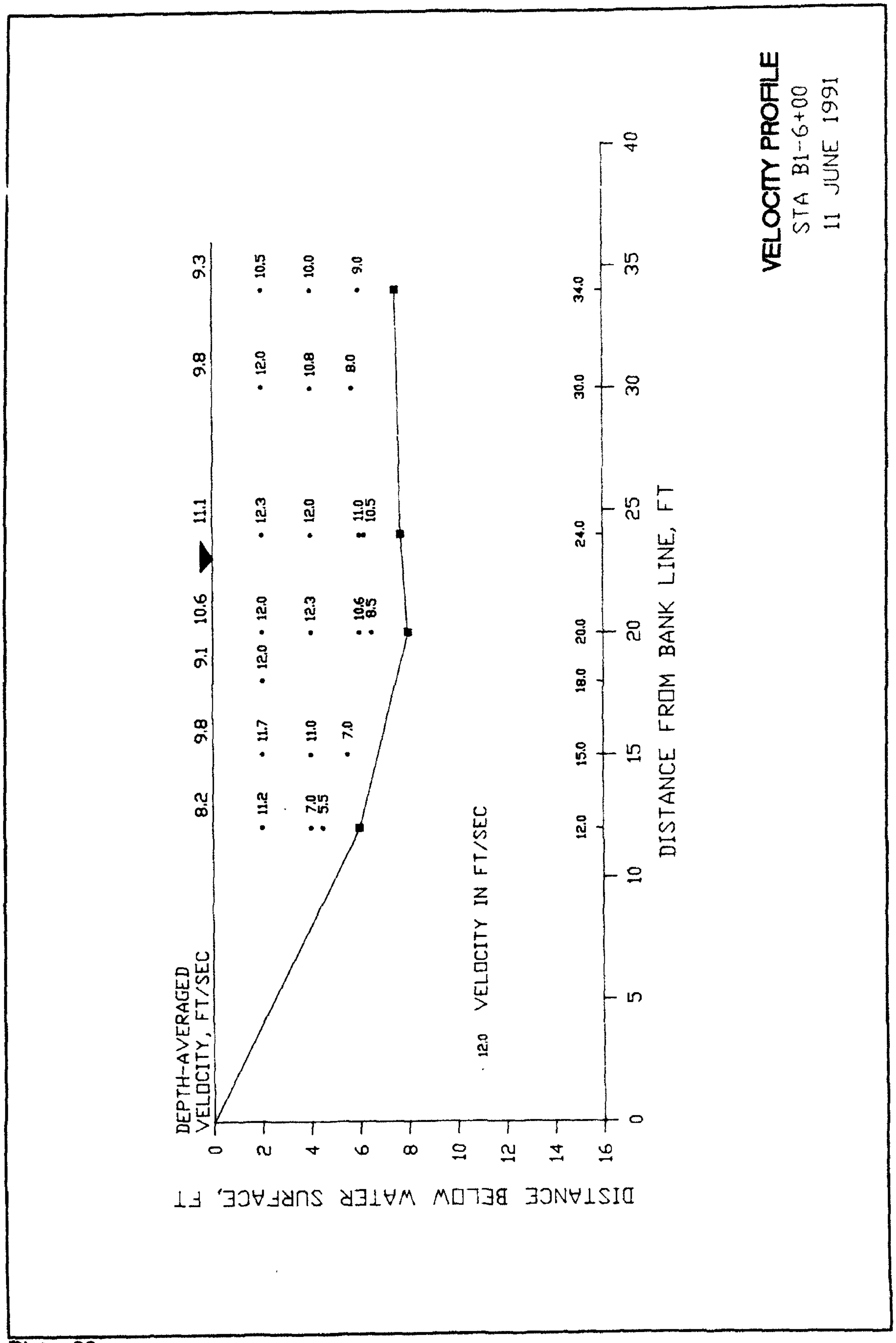
11 JUNE 1991

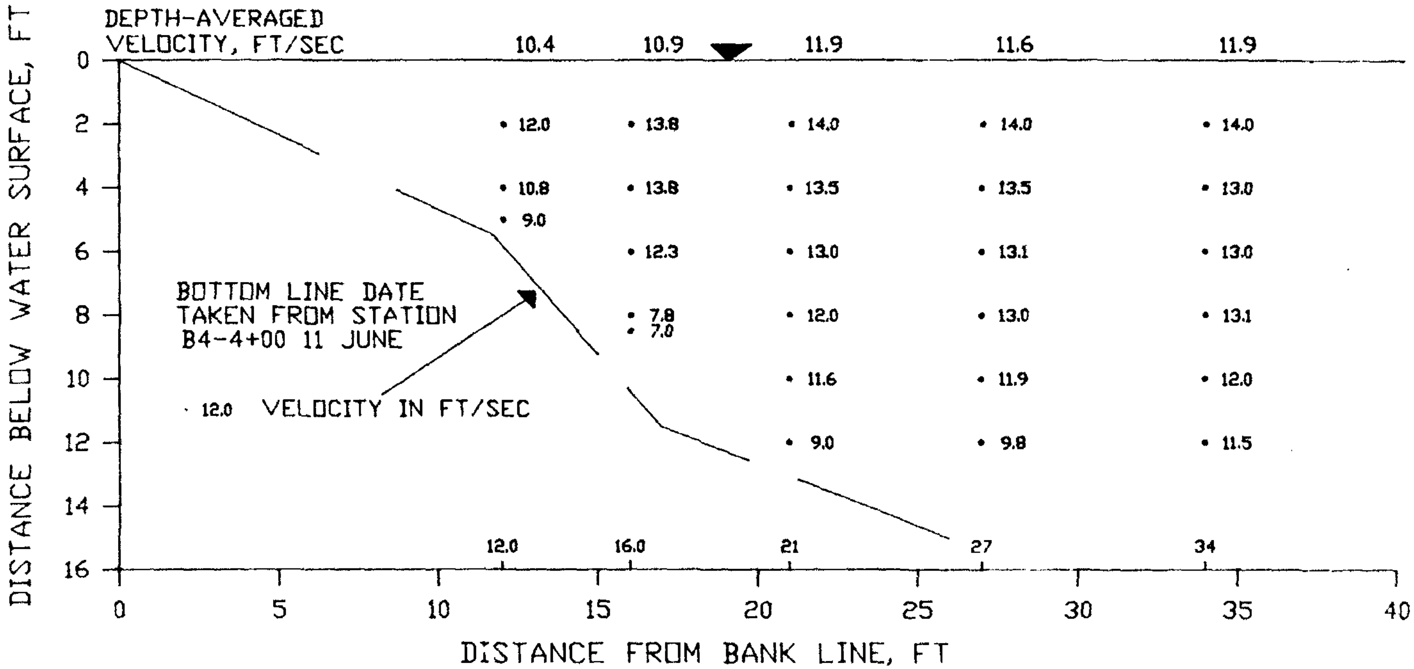


VELOCITY PROFILE

STA B1-5+00

11 JUNE 1991


VELOCITY PROFILE
STA B1-6+00
11 JUNE 1991
DEPTH-AVERAGED VELOCITY, FT/SEC
8.2
9.8
9.1
10.6
11.1
9.8
9.3
11.2
7.0
5.5
11.7
11.0
7.0
12.0
12.0
12.3
10.6
8.5
12.3
12.0
11.0
10.5
12.0
10.8
8.0
10.5
10.0
9.0
12.0
VELOCITY IN FT/SEC
12.0
15.0
18.0
20.0
24.0
30.0
34.0
0
5
10
15
20
25
30
35
40
DISTANCE FROM BANK LINE, FT
0
2
4
6
8
10
12
14
16
DISTANCE BELOW WATER SURFACE, FT



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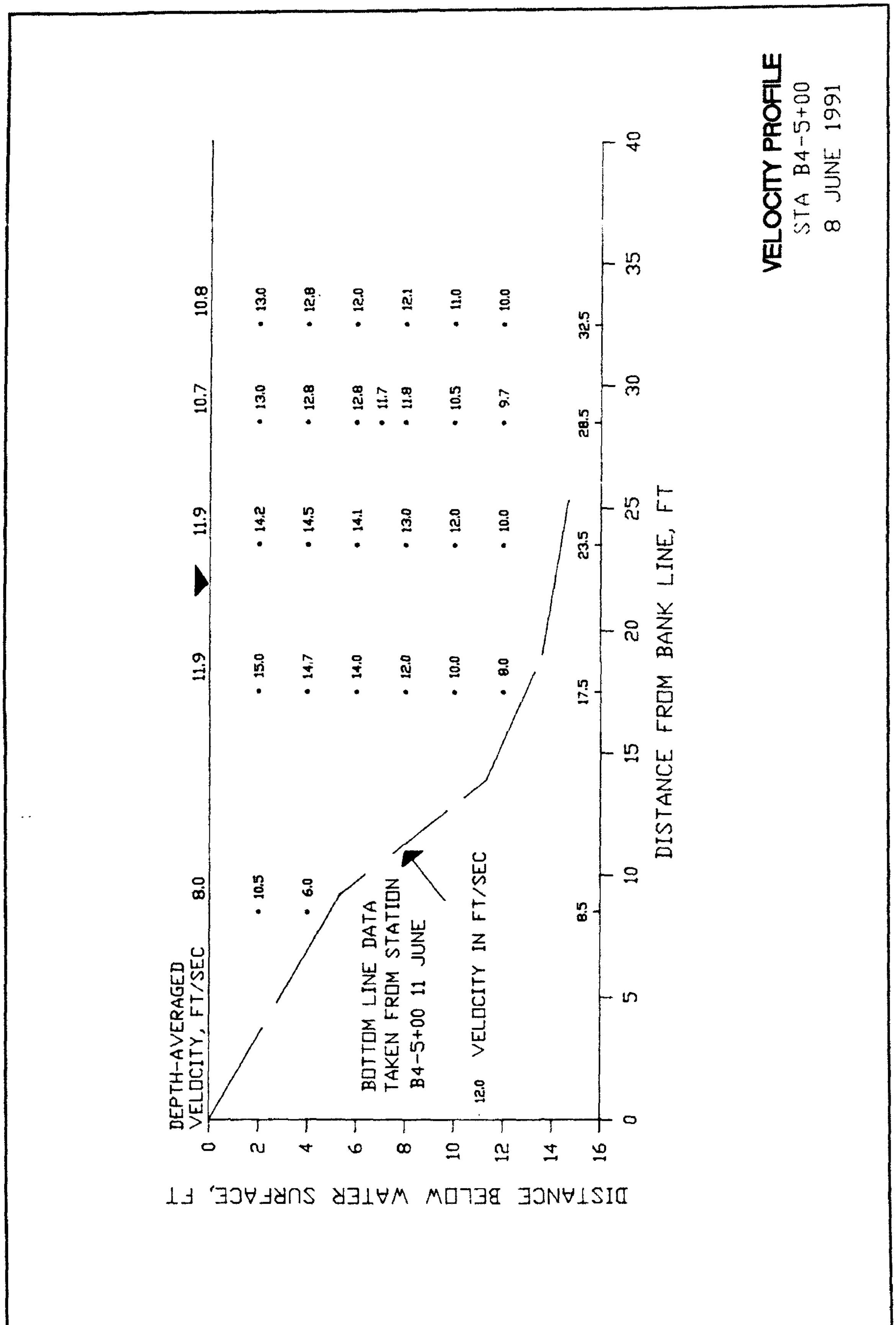
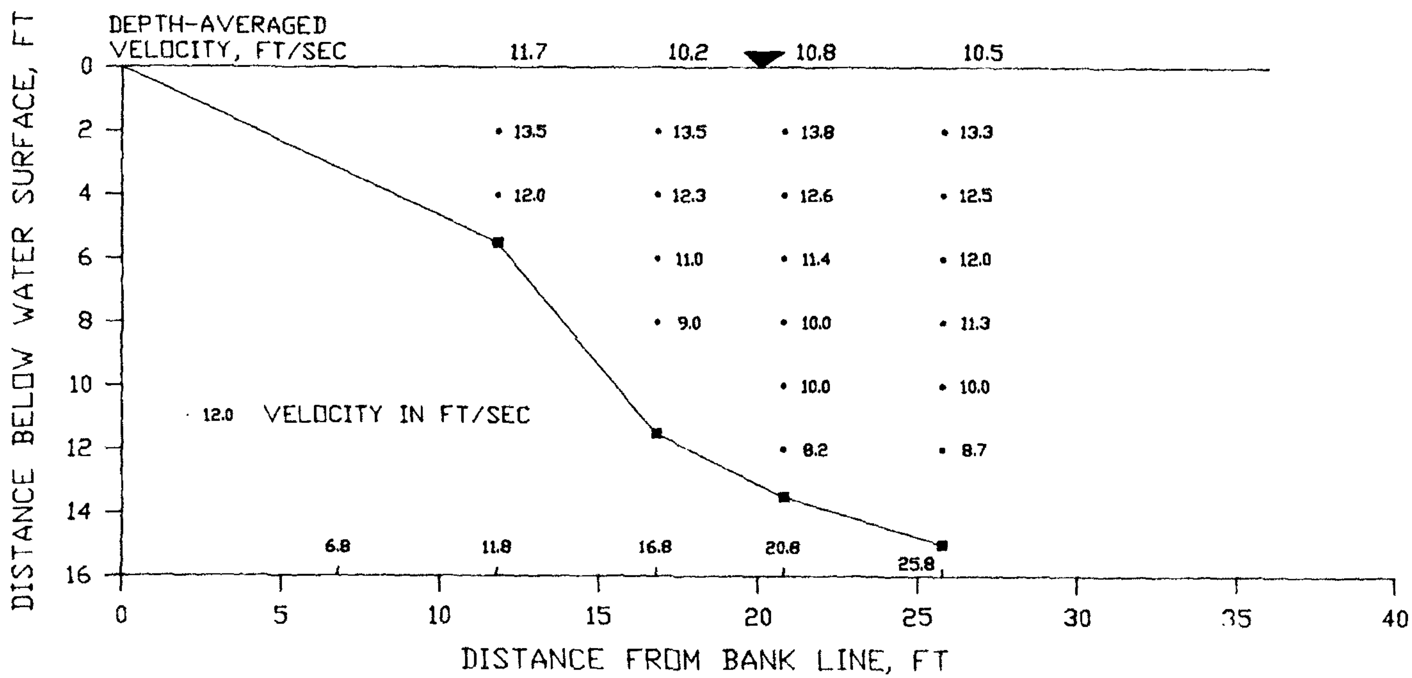


VELOCITY PROFILE
STA B4-5+00
8 JUNE 1991

Plate 28



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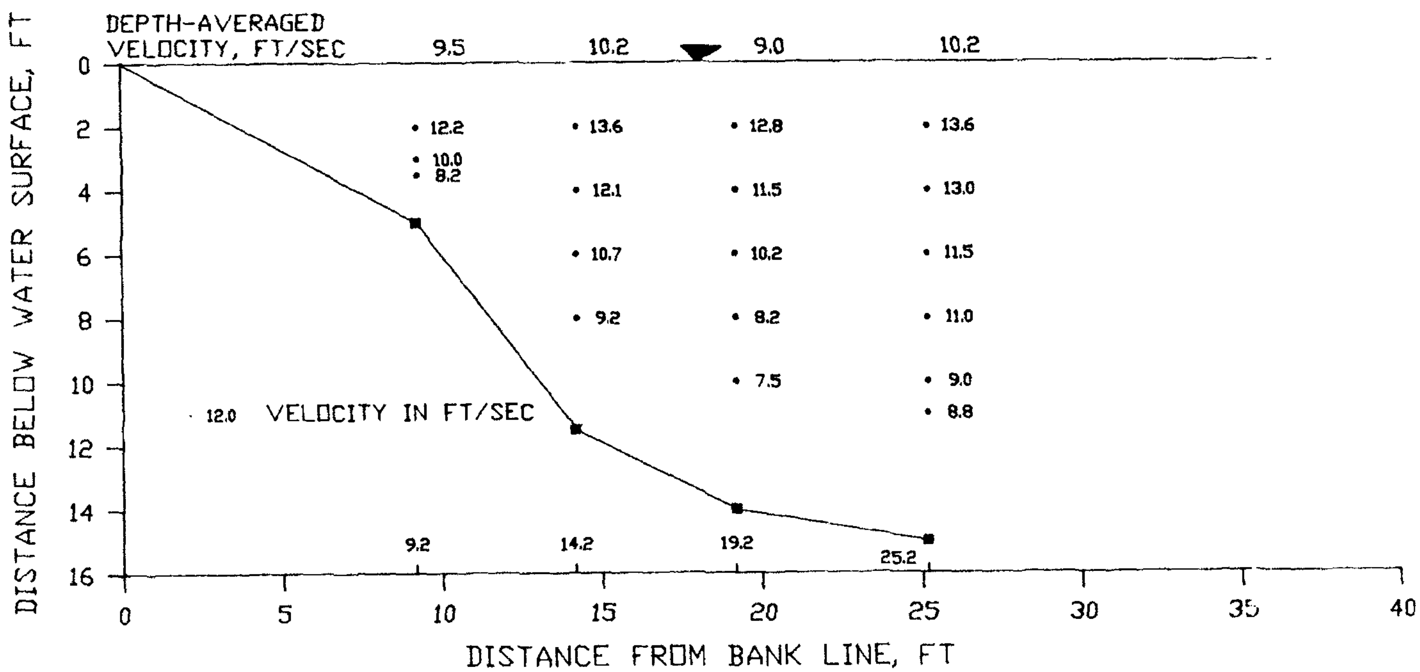
STA B4-4+00

11 JUNE 1991



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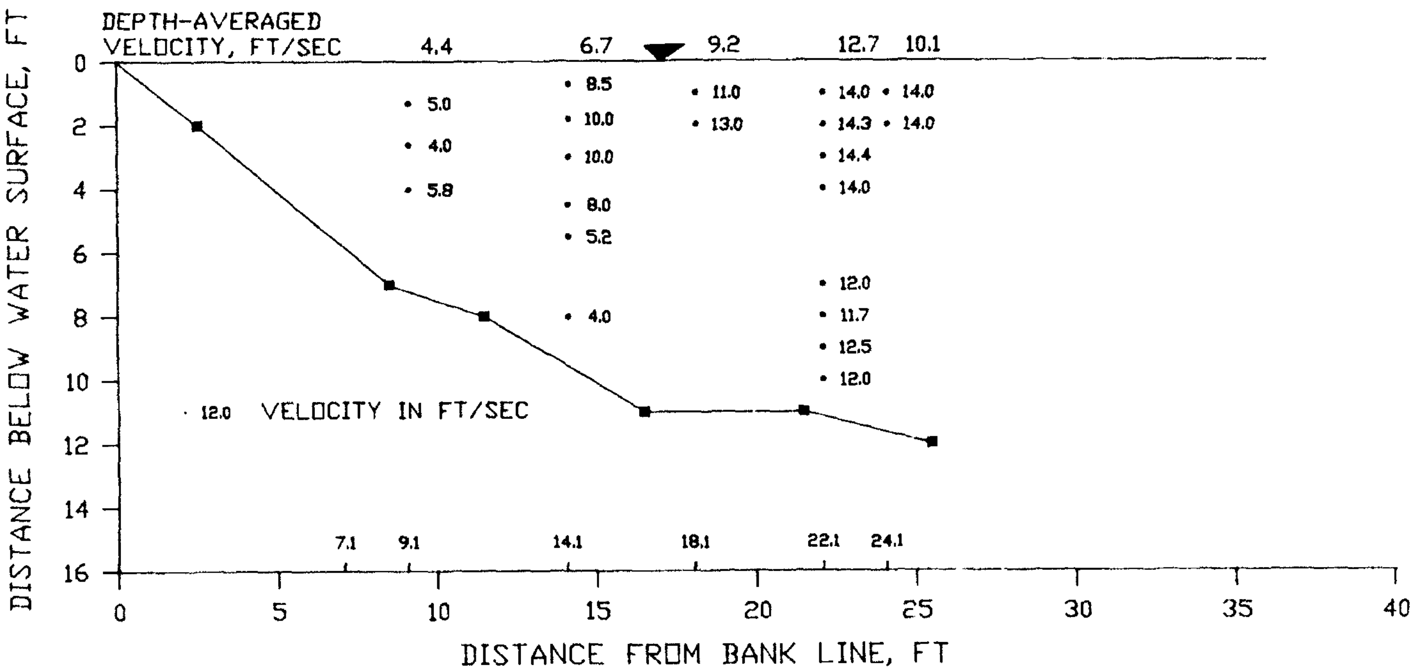
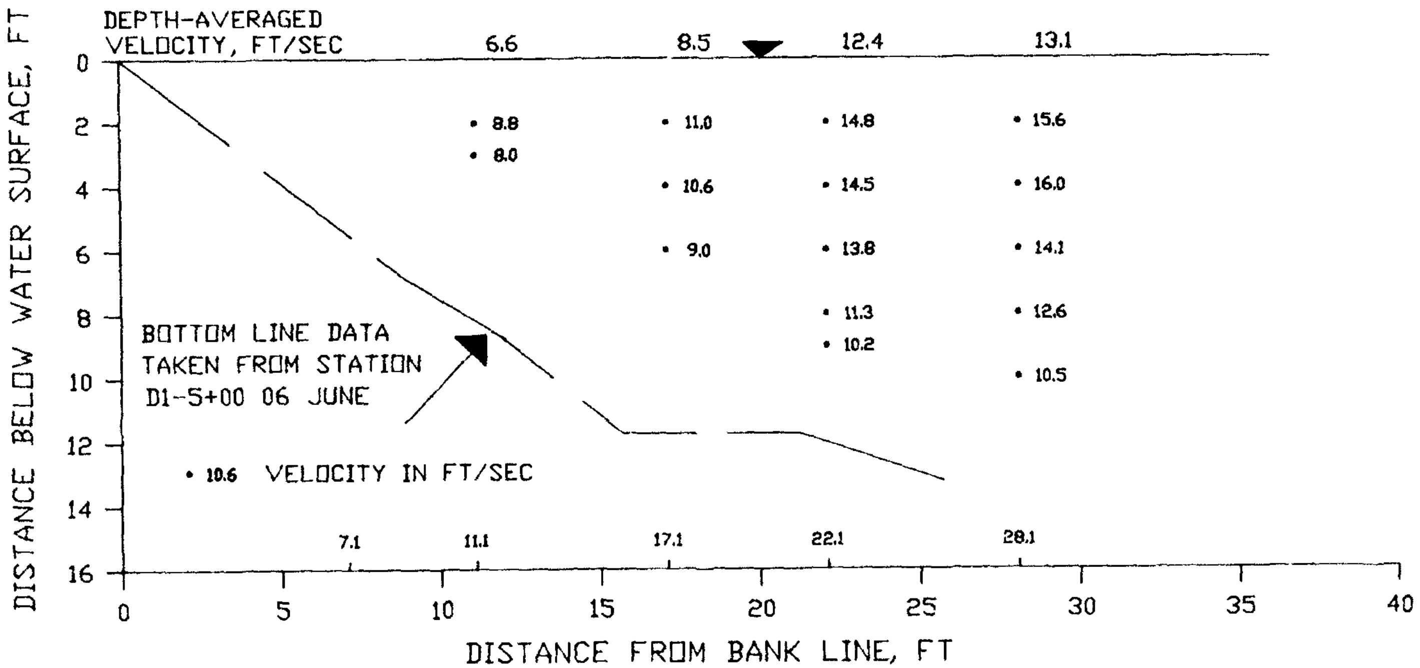
11 JUNE 1991



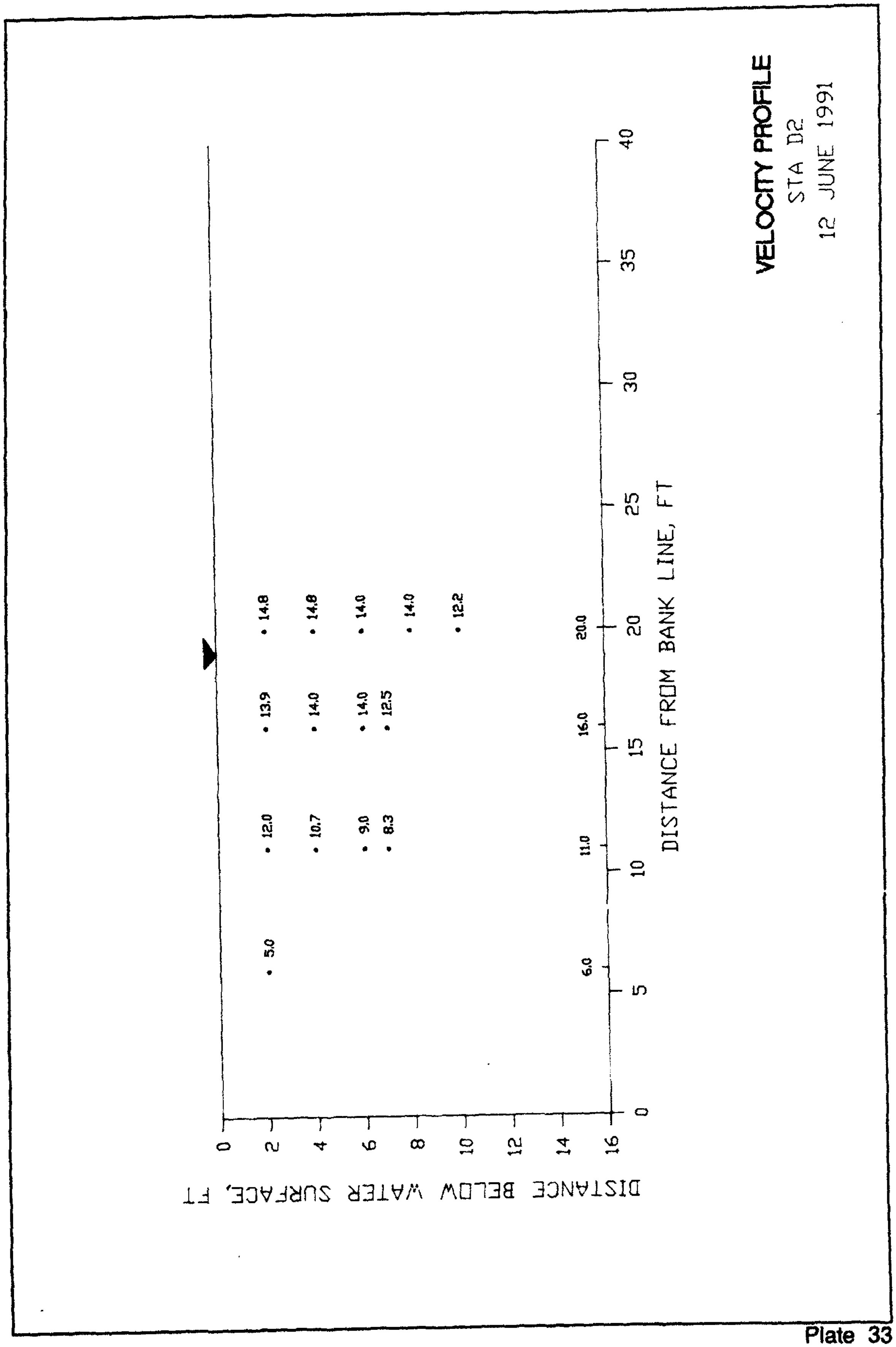
VELOCITY PROFILE

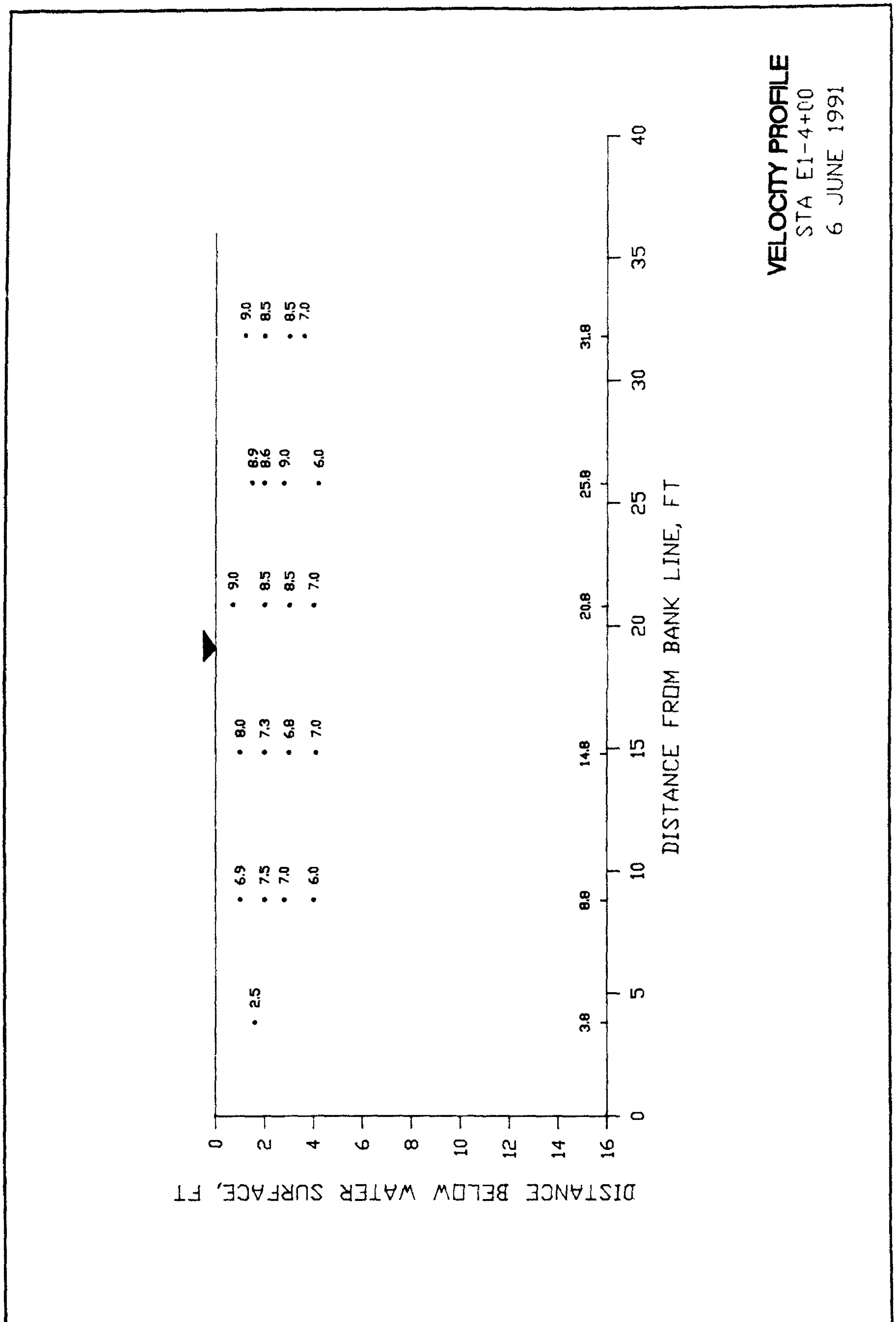
STA D1-5+00

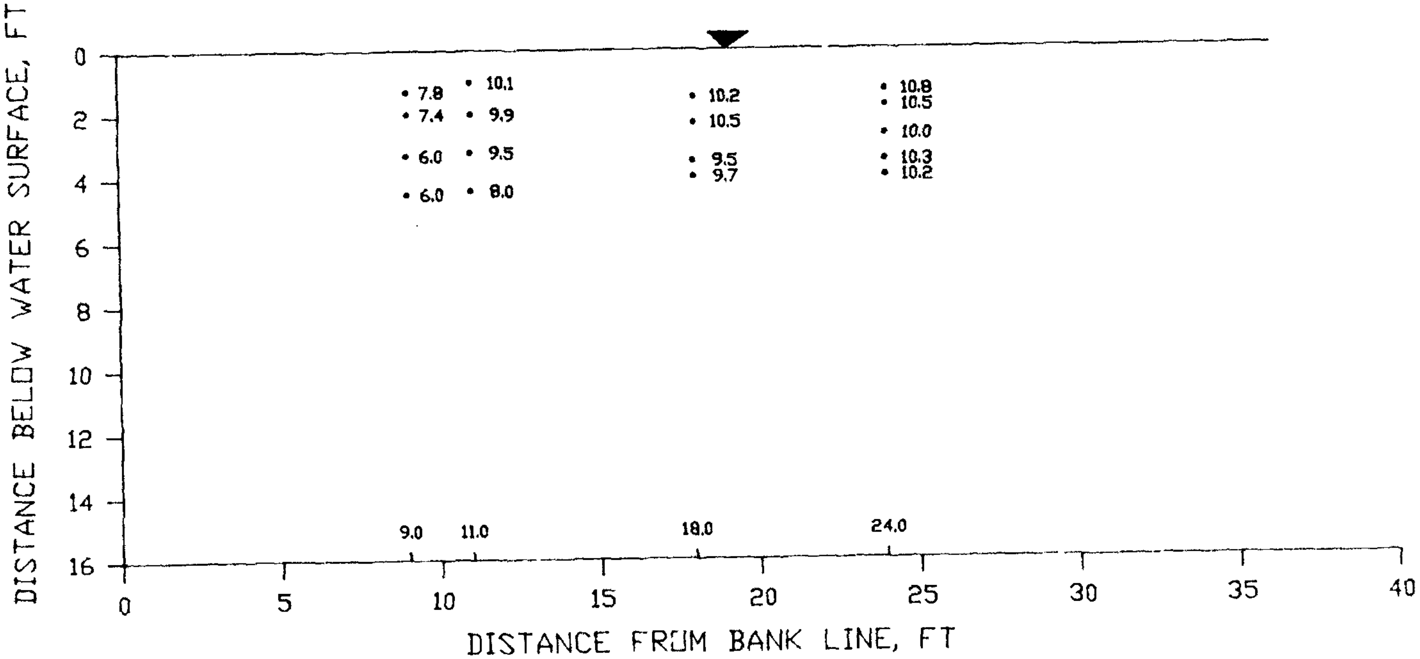
6 JUNE 1991



VELOCITY PROFILE
STA D1-5+00
12 JUNE 1991


VELOCITY PROFILE
STA D2
12 JUNE 1991
DISTANCE FROM BANK LINE, FT
DISTANCE BELOW WATER SURFACE, FT
0 5 10 15 20 25 30 35 40
0 2 4 6 8 10 12 14 16
6.0 11.0 16.0 20.0
5.0
12.0 10.7 9.0 8.3
13.9 14.0 14.0 12.5
14.8 14.8 14.0 14.0 12.2

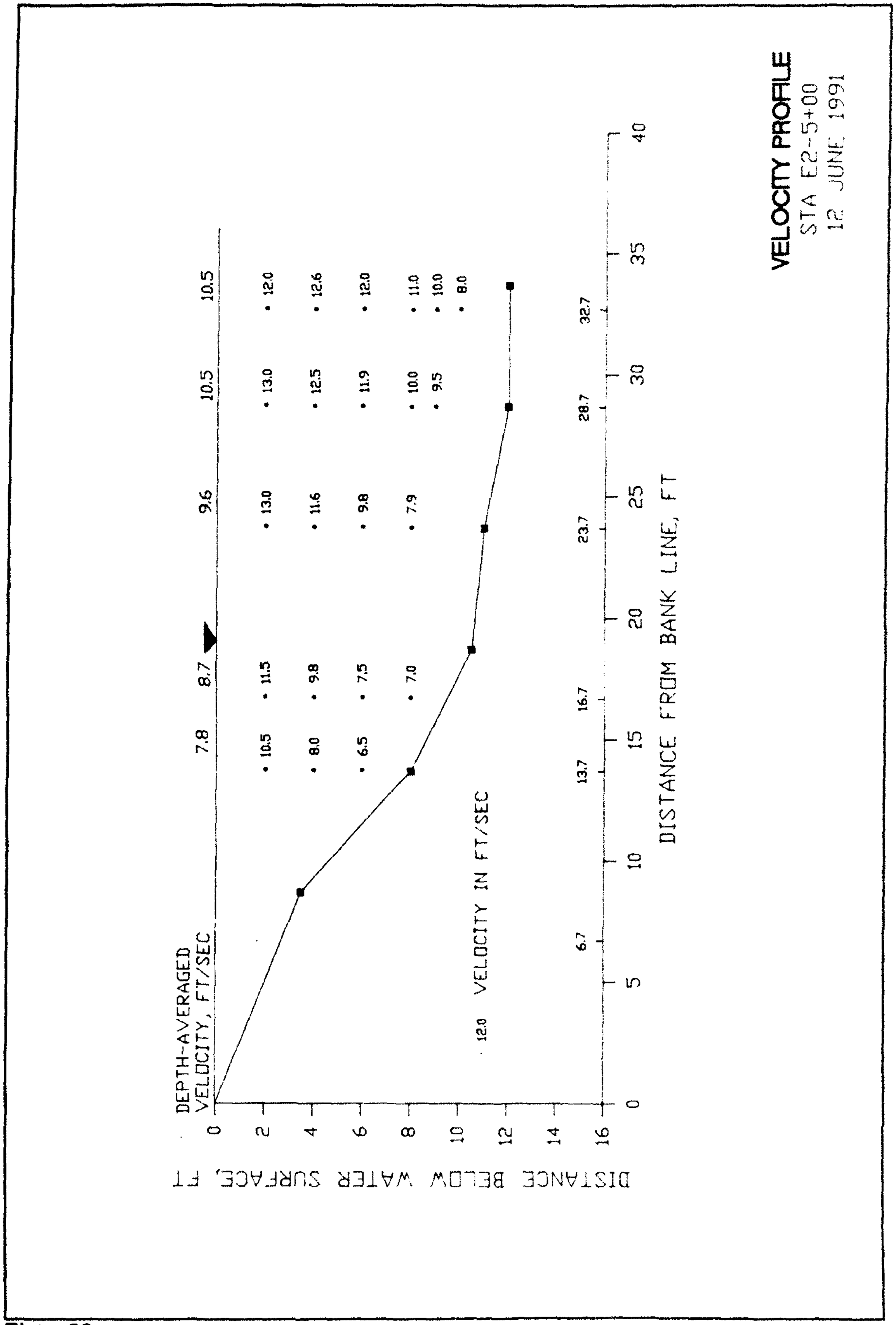

VELOCITY PROFILE
STA E1-4+00
6 JUNE 1991
DISTANCE FROM BANK LINE, FT
DISTANCE BELOW WATER SURFACE, FT

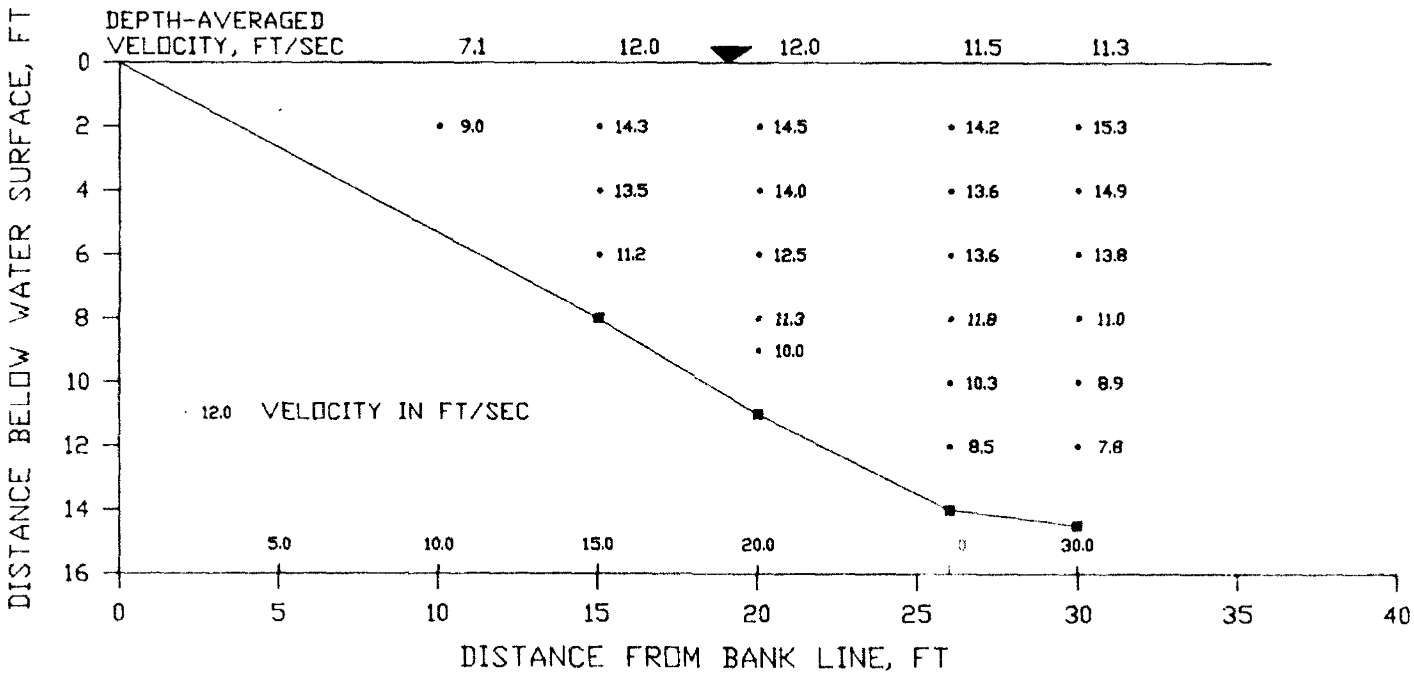


VELOCITY PROFILE

STA E1-5+00

6 JUNE 1991


VELOCITY PROFILE
STA E2-5+00
12 JUNE 1991
DEPTH-AVERAGED VELOCITY, FT/SEC
7.8
8.7
9.6
10.5
10.5
12.0 VELOCITY IN FT/SEC
DISTANCE BELOW WATER SURFACE, FT
DISTANCE FROM BANK LINE, FT
6.7
13.7
16.7
23.7
28.7
32.7



VELOCITY PROFILE

STA E2-5+70

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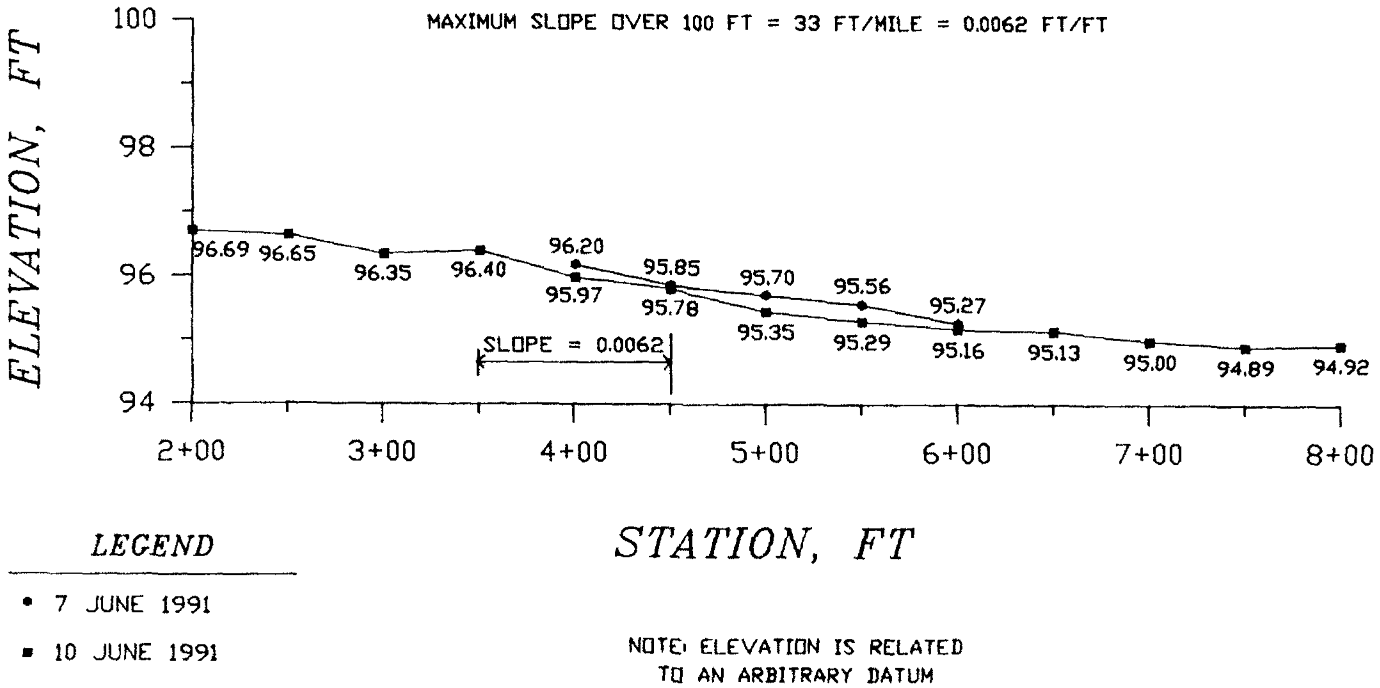
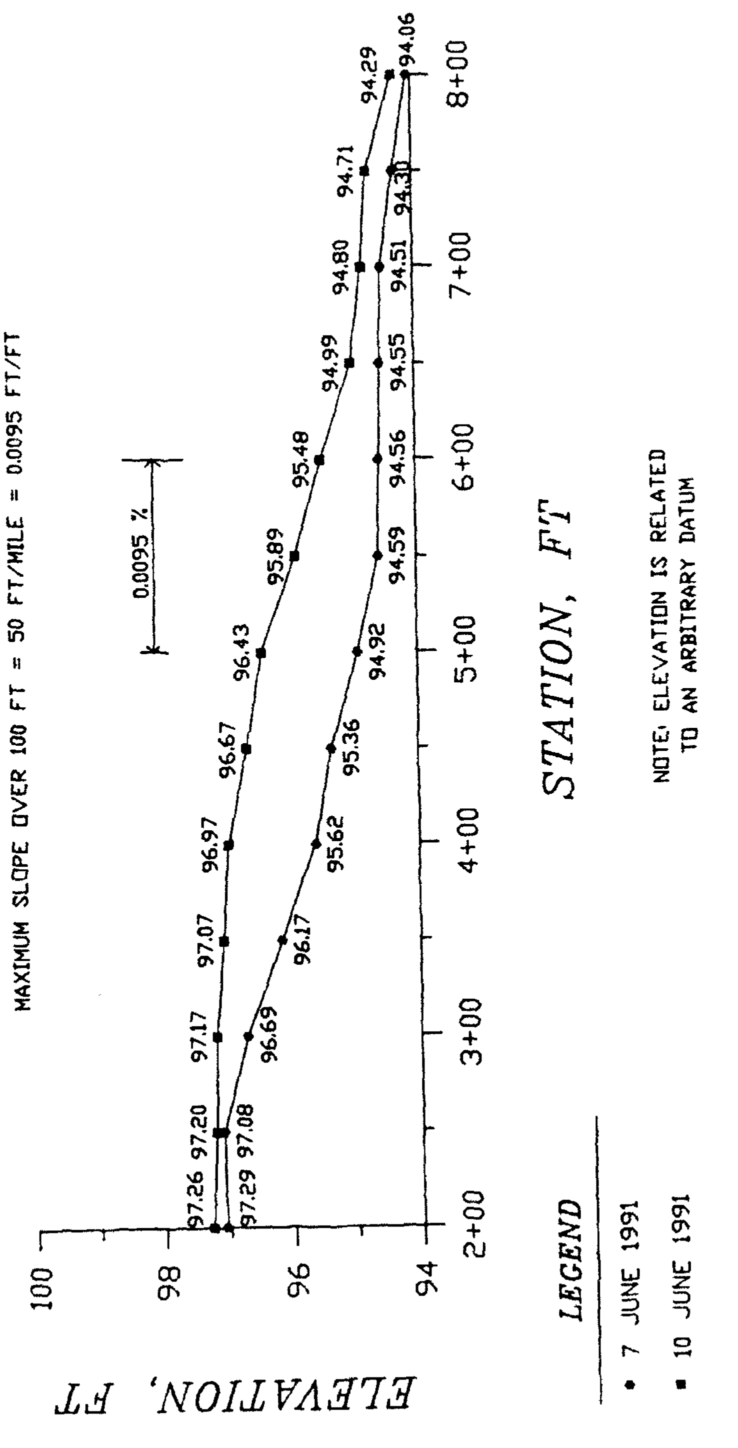
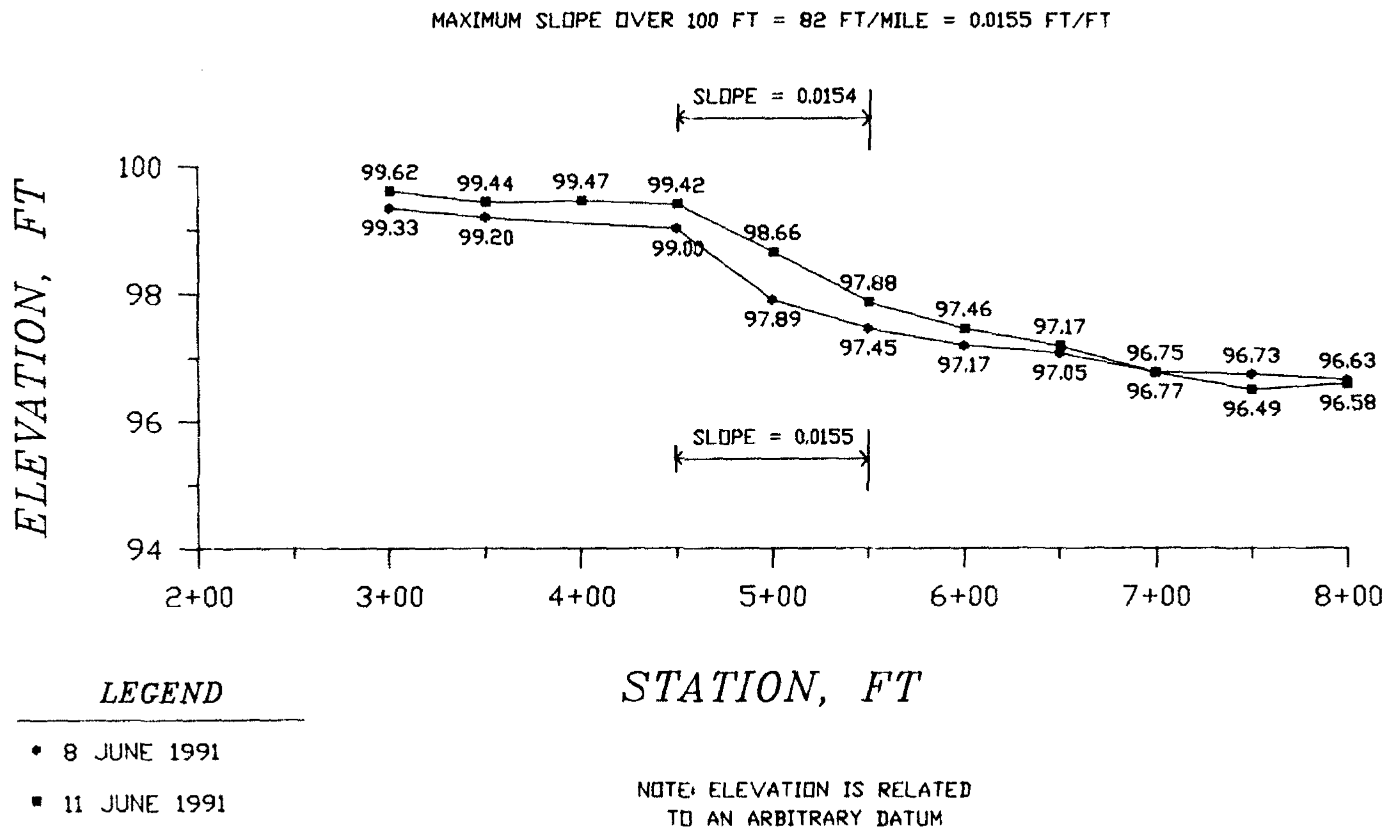


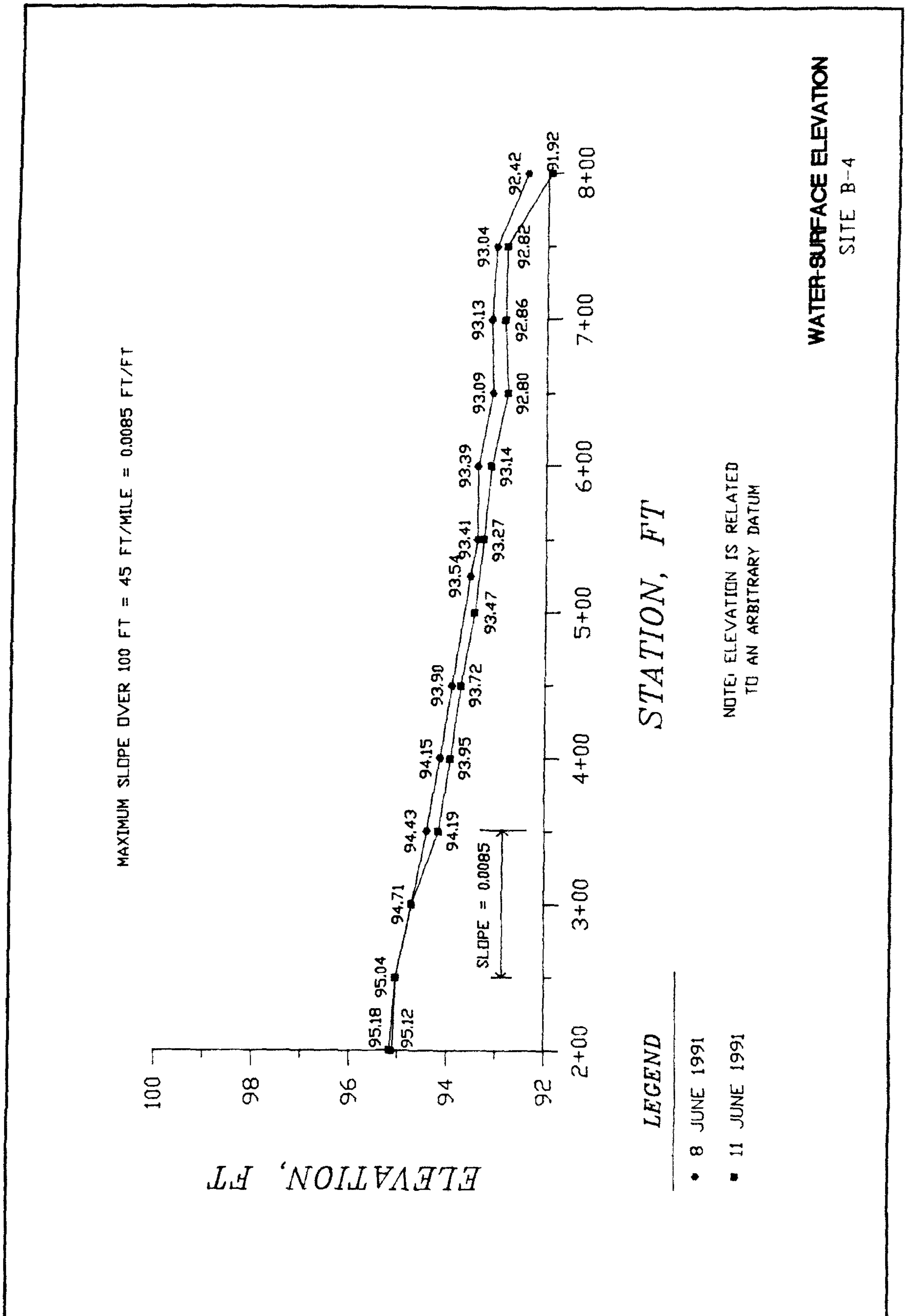
WATER-SURFACE ELEVATION
SITE A-1

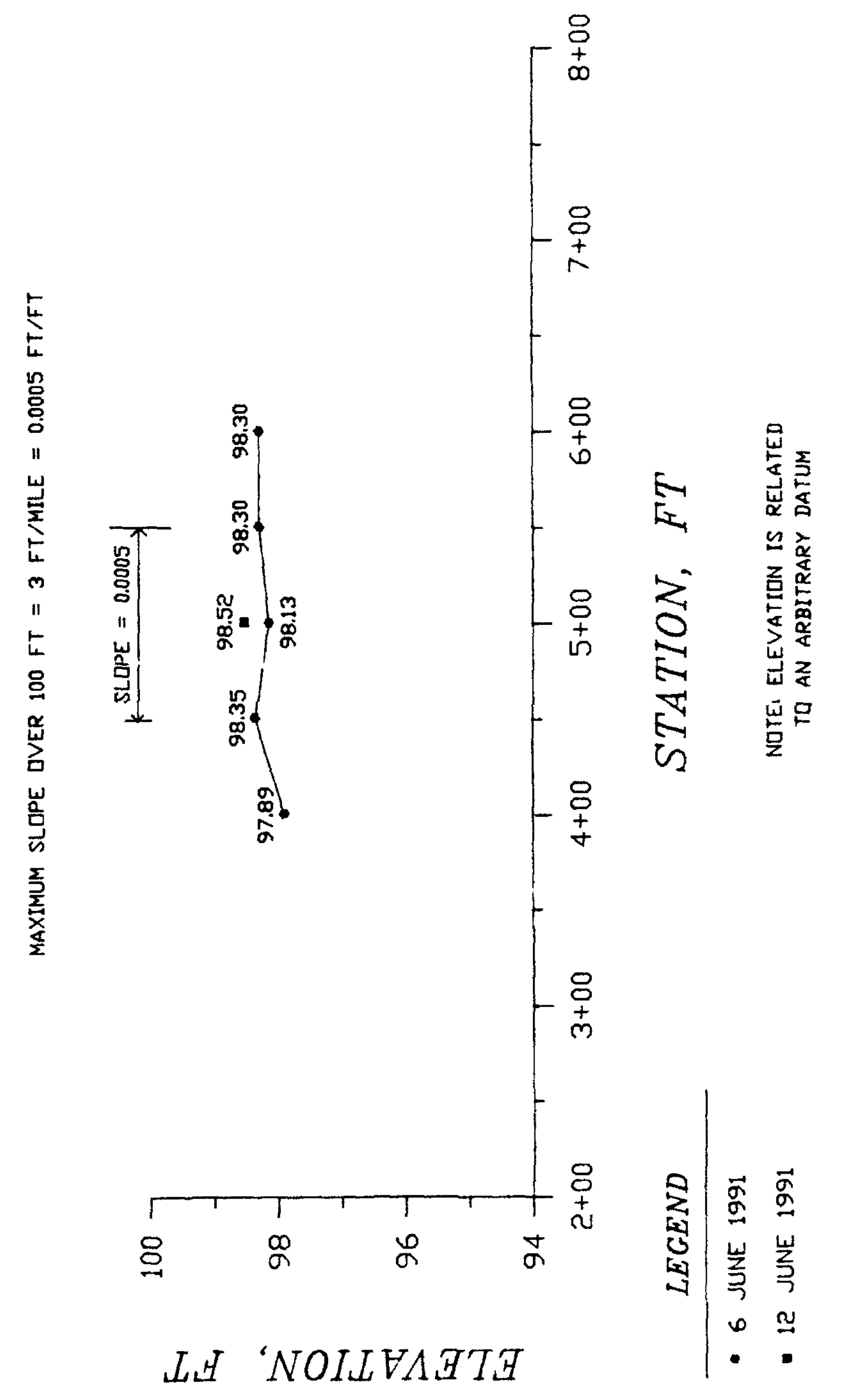


WATER-SURFACE ELEVATION
SITE A-2

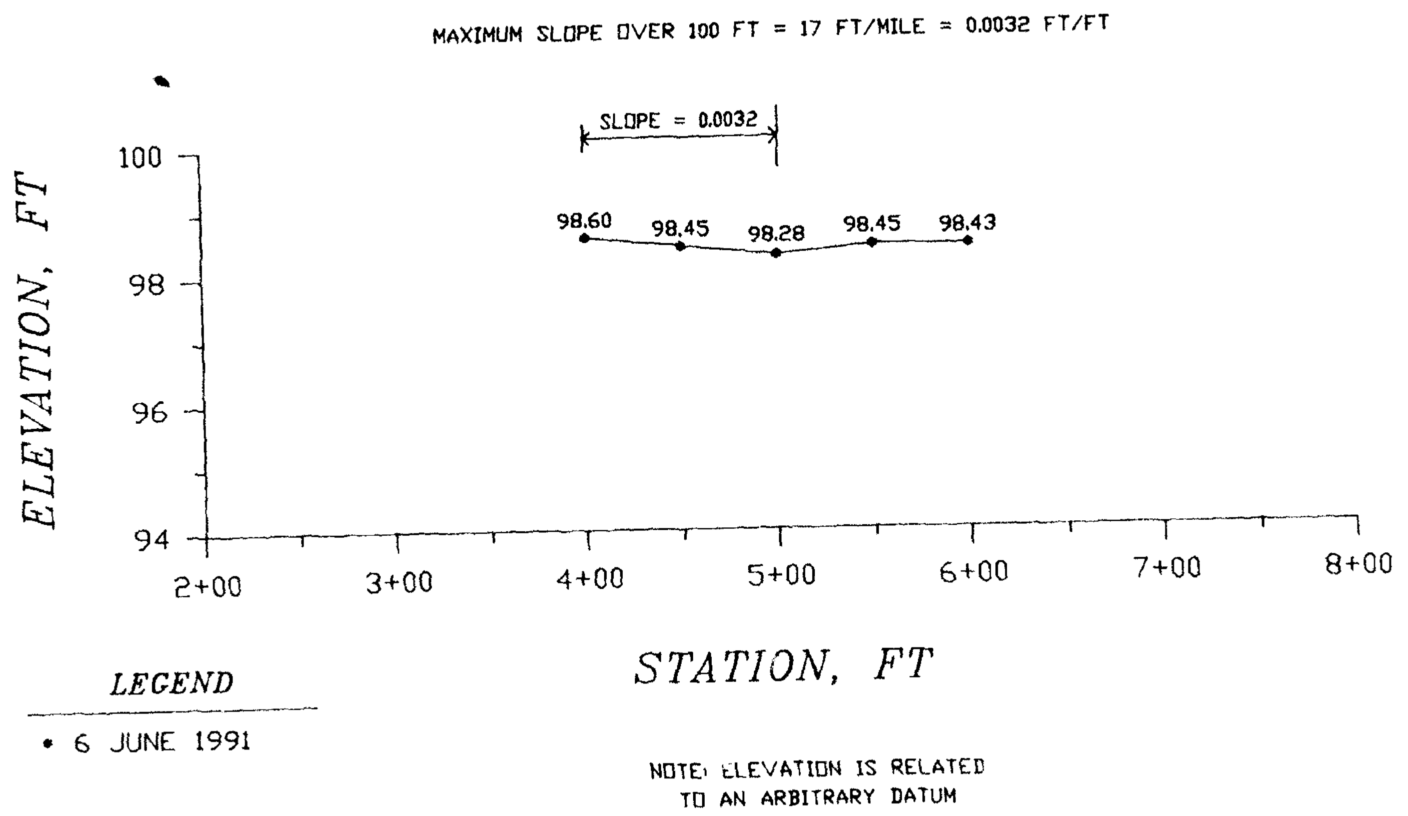


WATER-SURFACE ELEVATION
SITE B-1

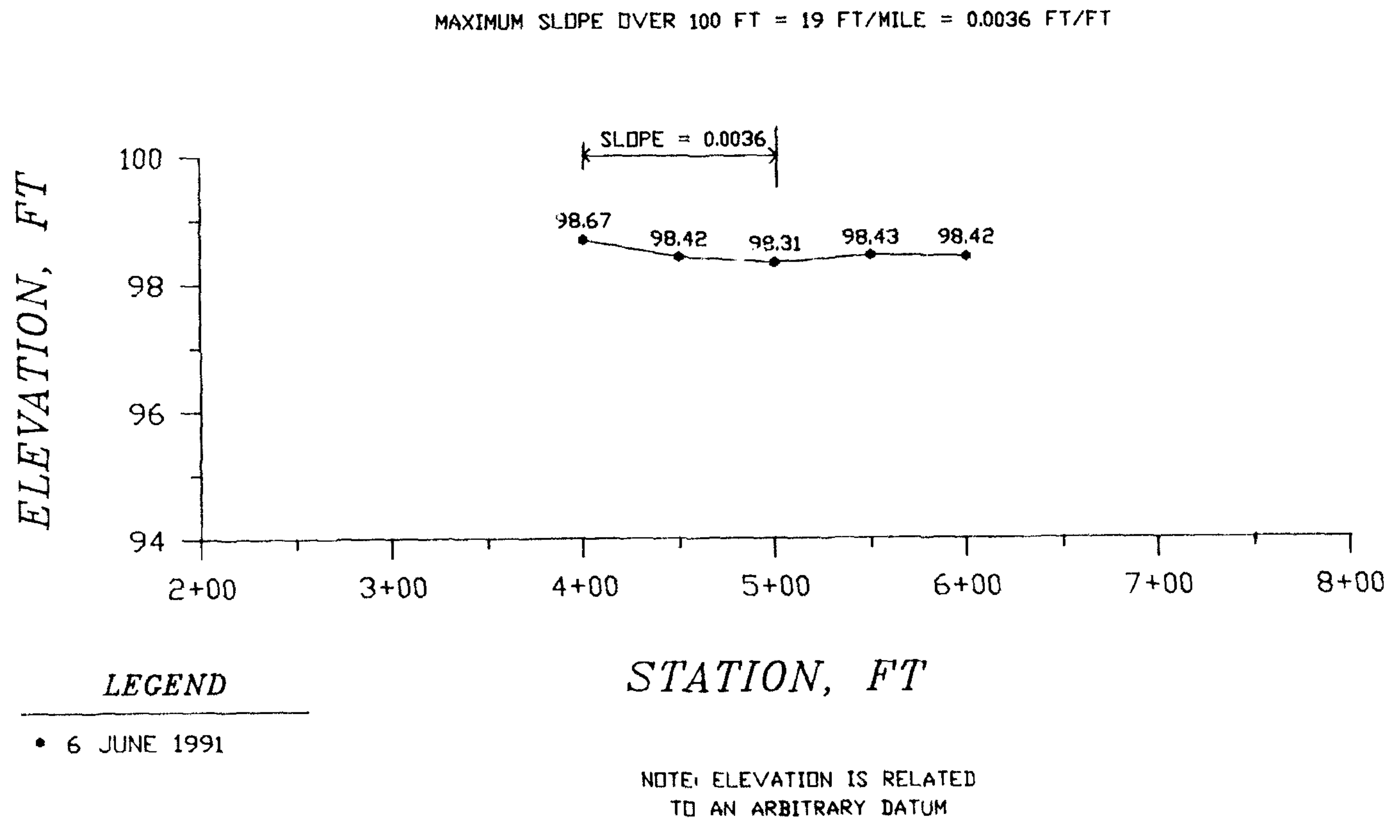

WATER-SURFACE ELEVATION
SITE B-4
MAXIMUM SLOPE OVER 100 FT = 45 FT/MILE = 0.0085 FT/FT
ELEVATION, FT
STATION, FT
100
98
96
94
92
2+00
3+00
4+00
5+00
6+00
7+00
8+00
95.18
95.12
95.04
94.71
94.43
94.19
94.15
93.95
93.90
93.72
93.47
93.54
93.41
93.27
93.39
93.14
93.09
92.80
93.13
92.86
93.04
92.82
92.42
91.92
SLOPE = 0.0085
NOTE: ELEVATION IS RELATED
TO AN ARBITRARY DATUM
LEGEND
• 8 JUNE 1991
▪ 11 JUNE 1991



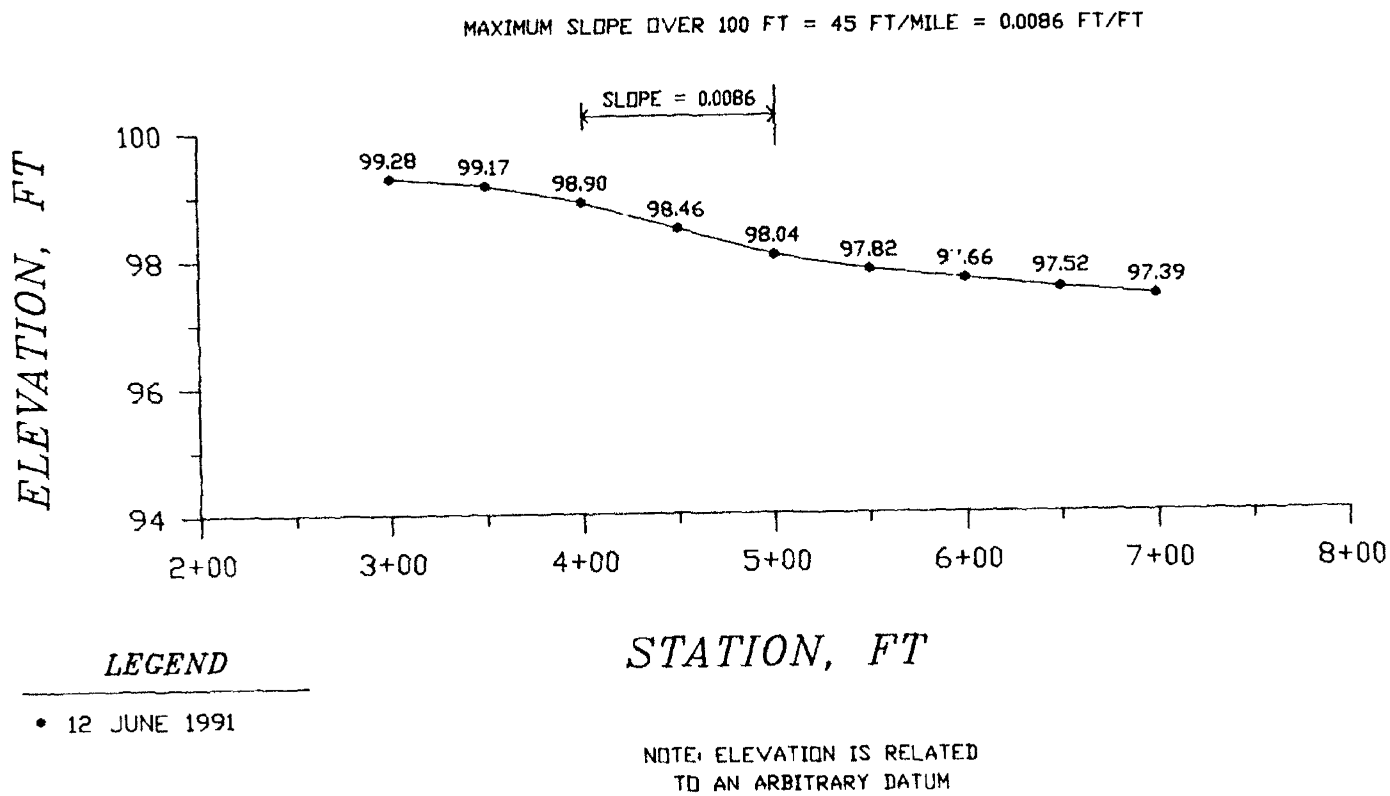
WATER-SURFACE ELEVATION
SITE D-1 (TRIAL 1)



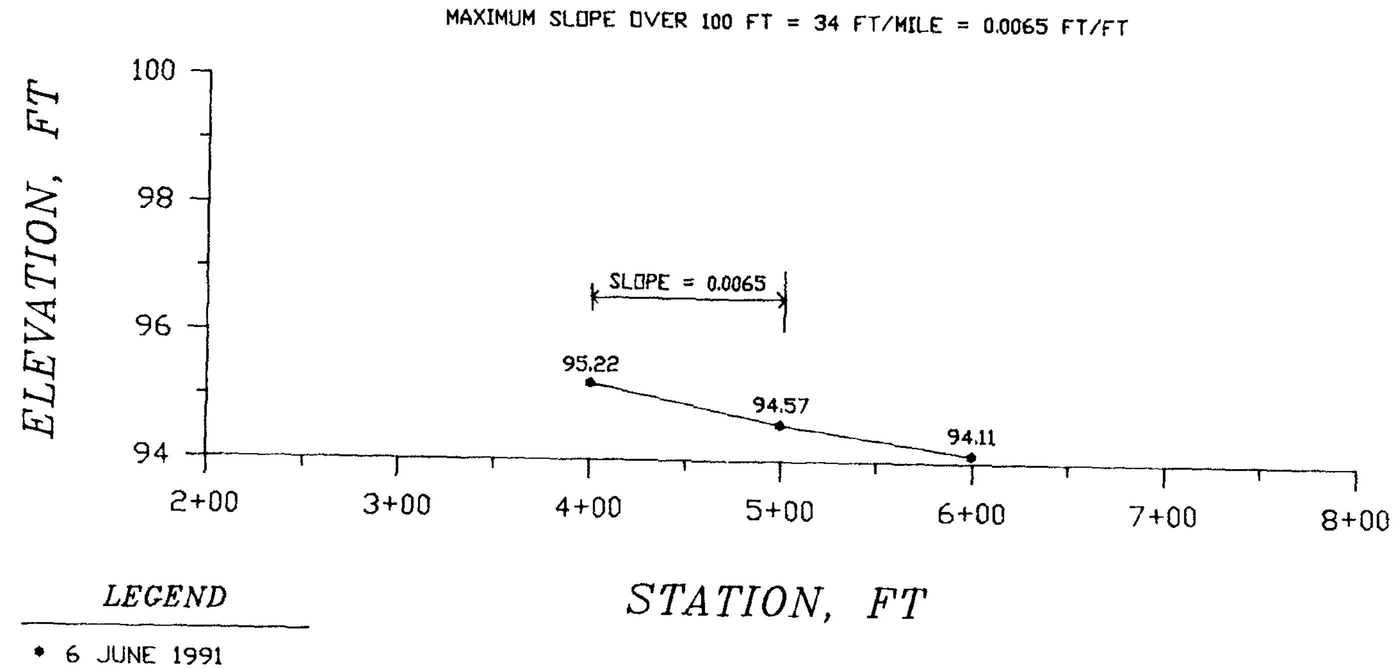
WATER-SURFACE ELEVATION
SITE D-1 (TRIAL 2)



WATER-SURFACE ELEVATION
SITE D-1 (TRIAL 3)



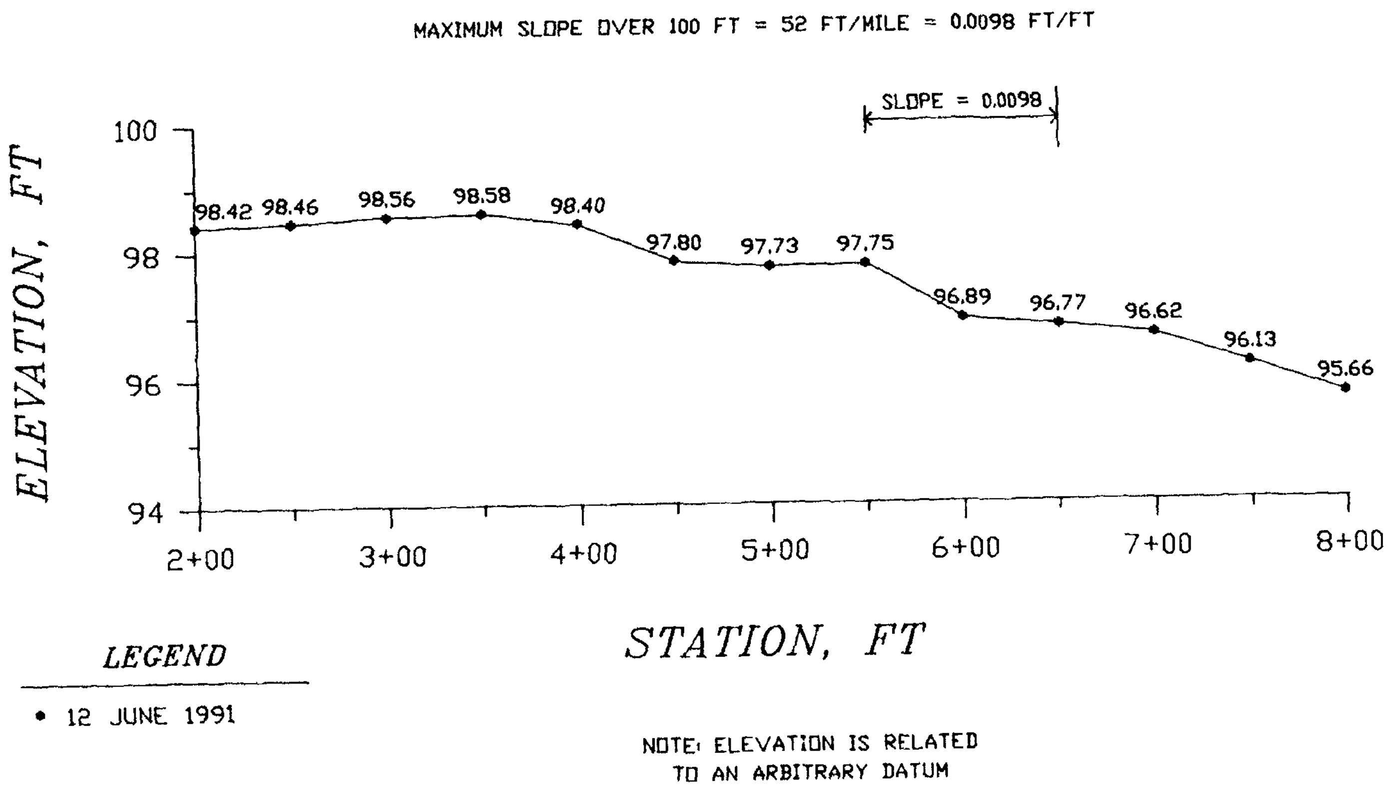
WATER-SURFACE ELEVATION
SITE D-2



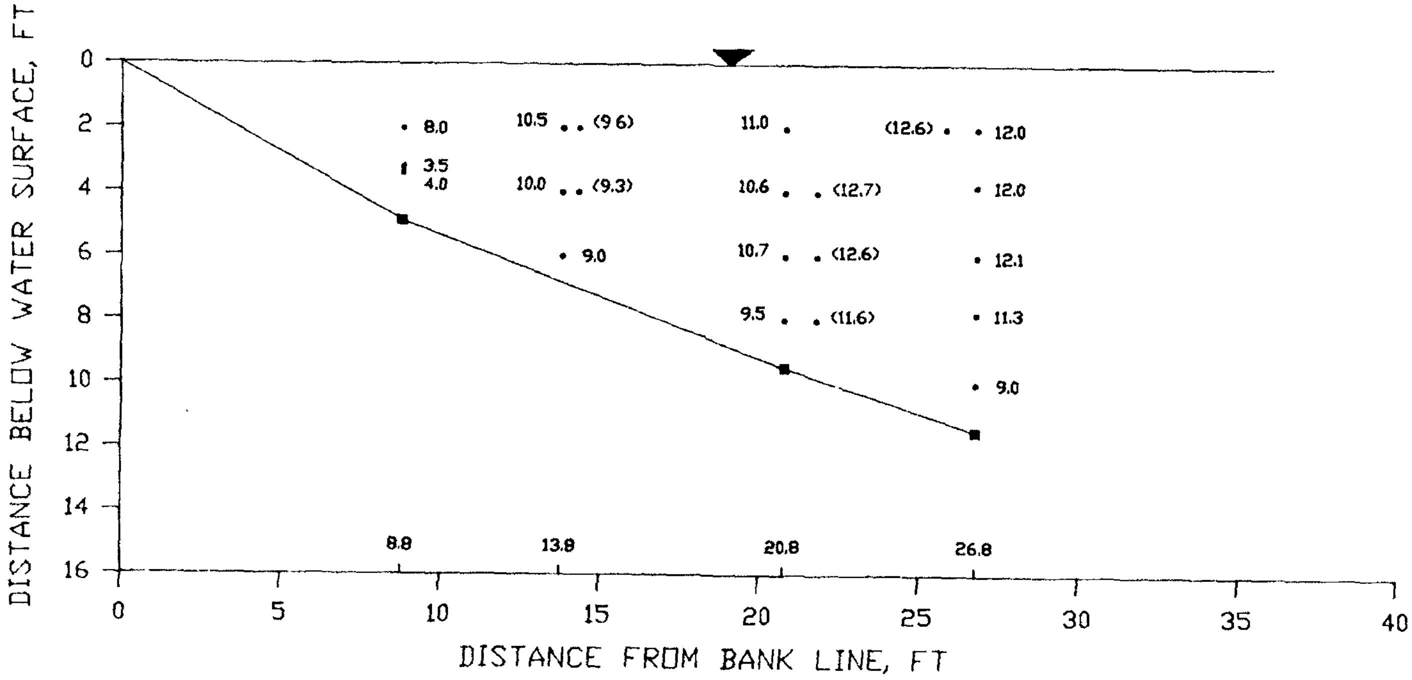
NOTE: ELEVATION IS RELATED TO AN ARBITRARY DATUM

WATER-SURFACE ELEVATION

SITE E-1

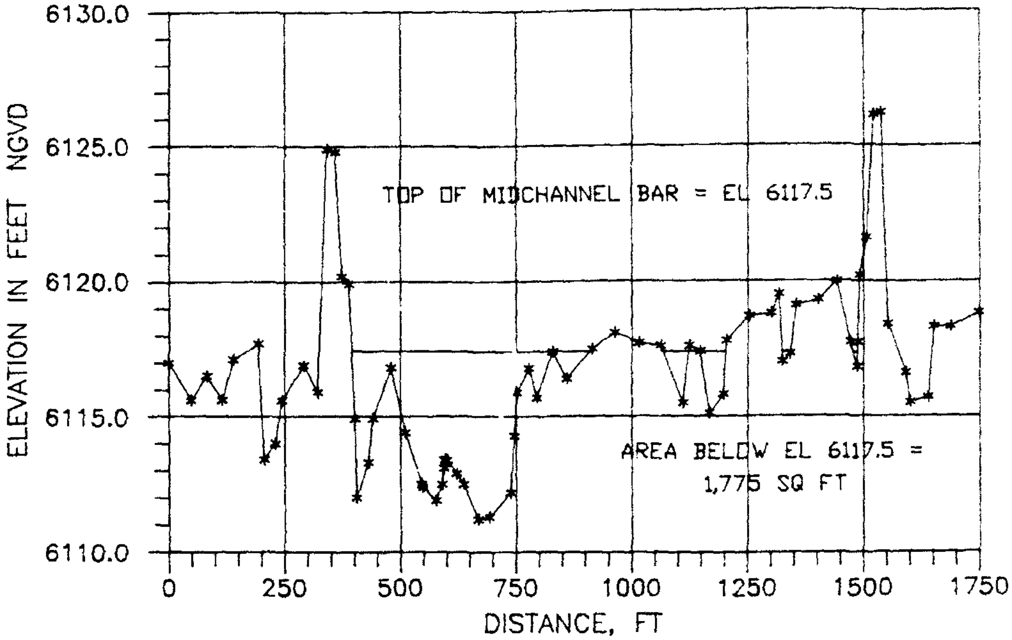


WATER-SURFACE ELEVATION
SITE E-2

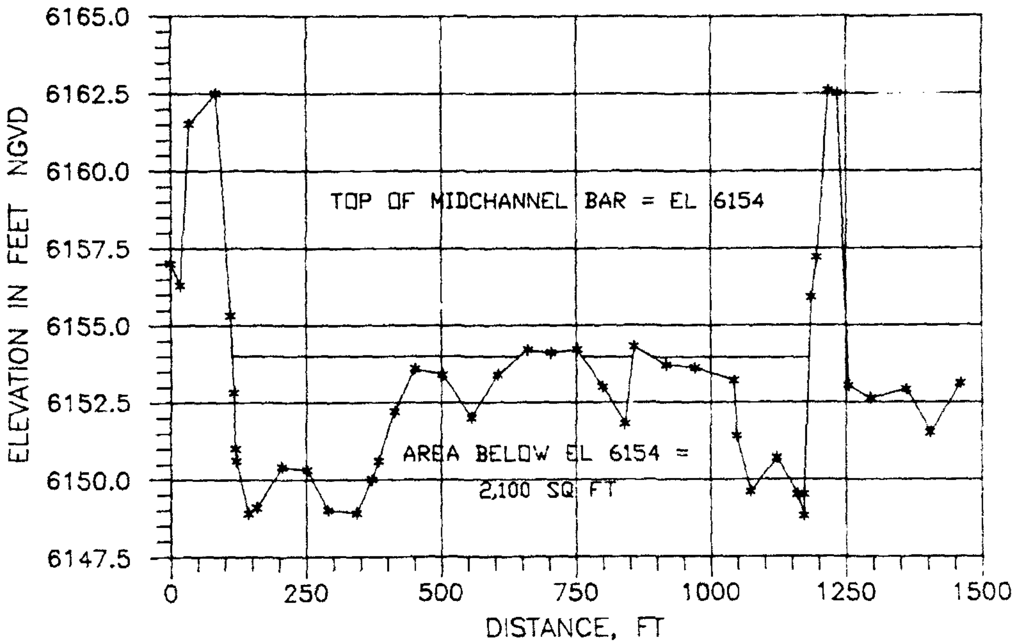


(12.6) PRICE VELOCITY METER READINGS

VELOCITY METER READINGS
STA A2-4+00
7 JUNE 1991



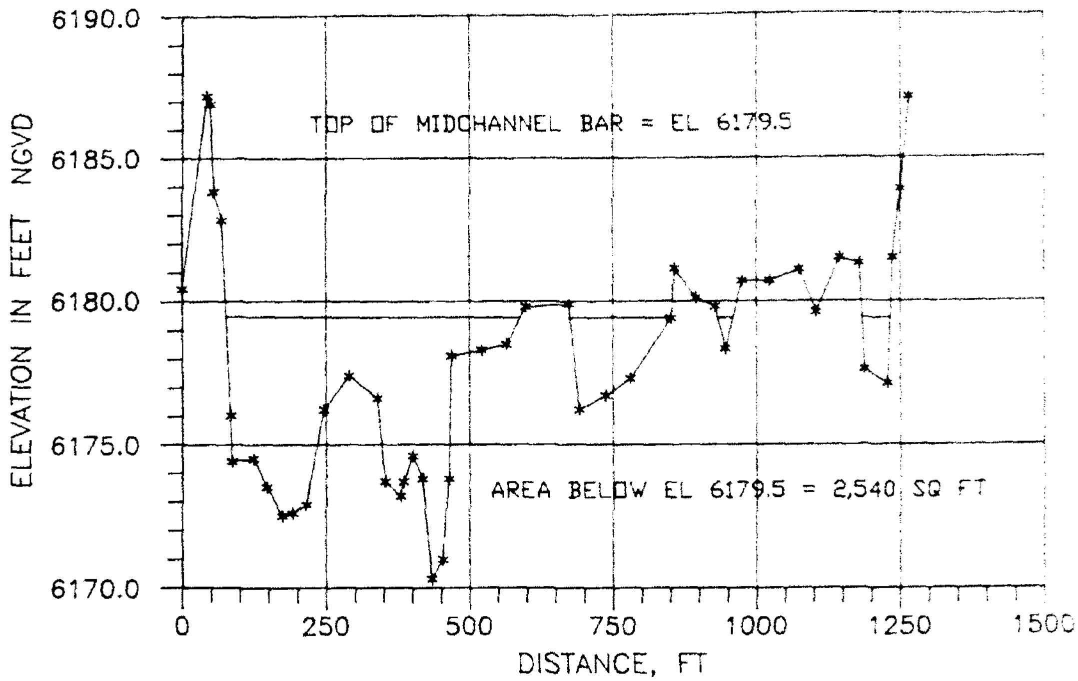
STA 5+05



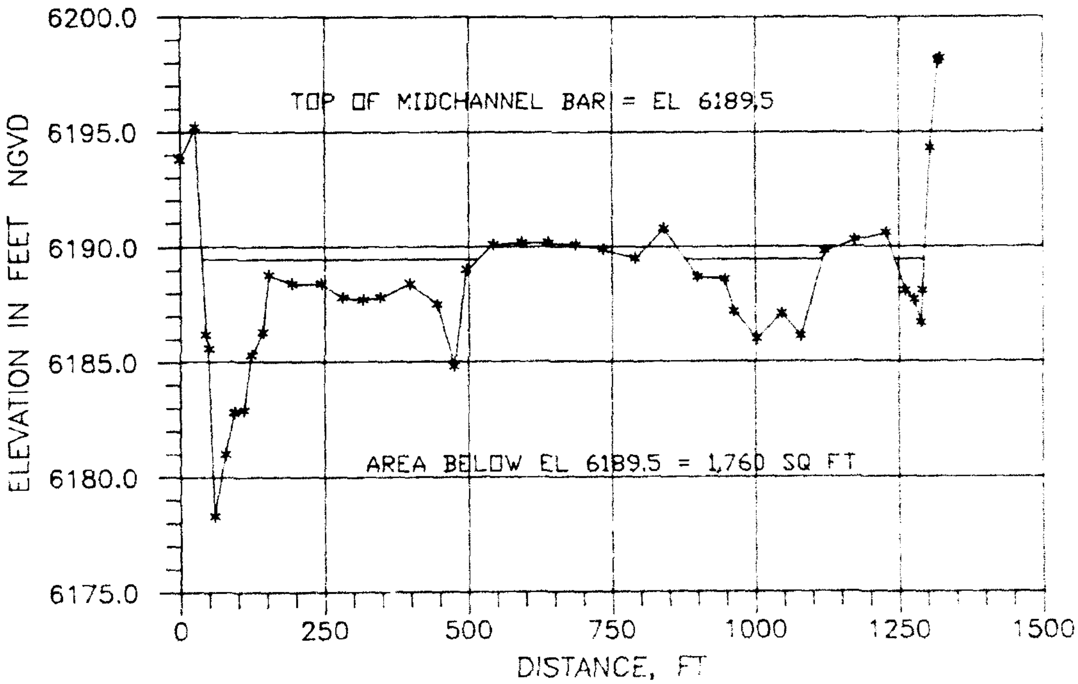
STA 5+95

CROSS SECTIONS

STA 5+05 AND 5+95



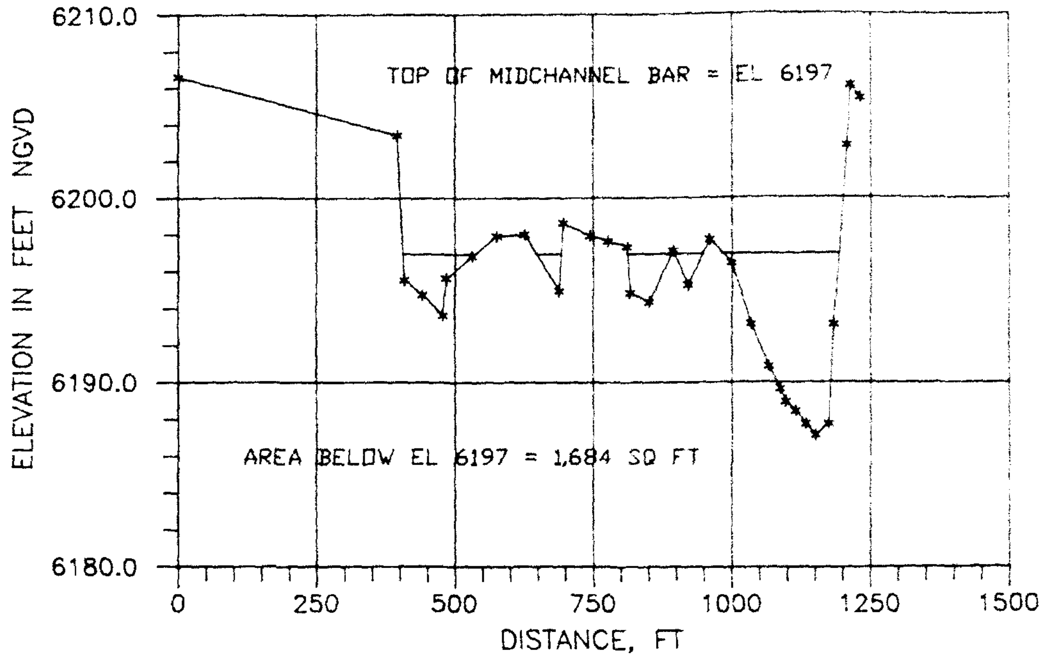
STA 6+59



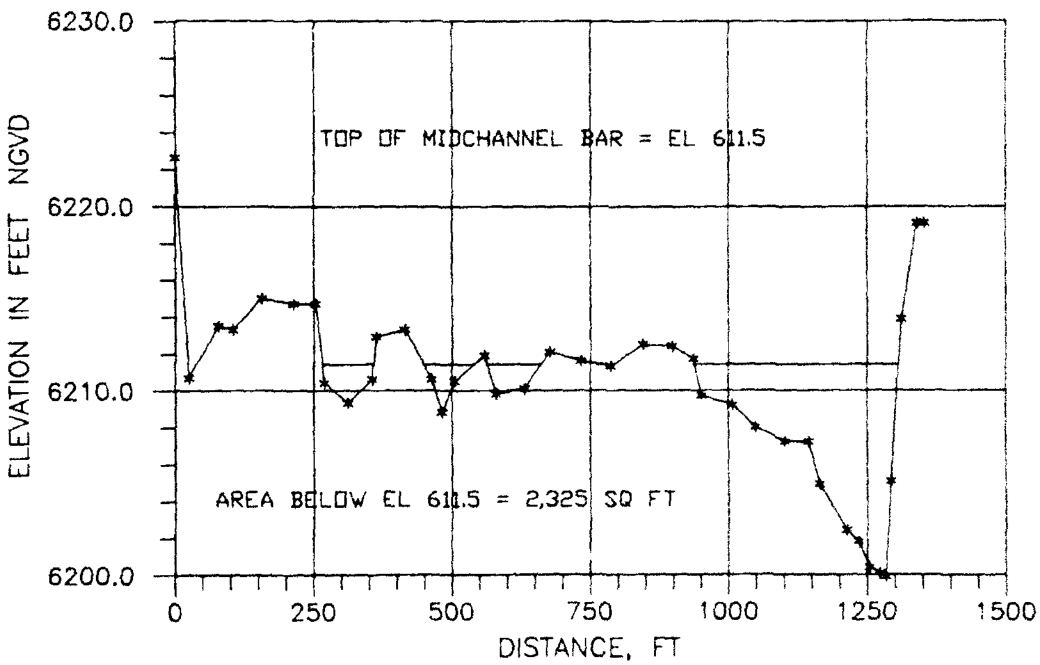
STA 6+86

CROSS SECTIONS

STA 6+59 AND 6+86



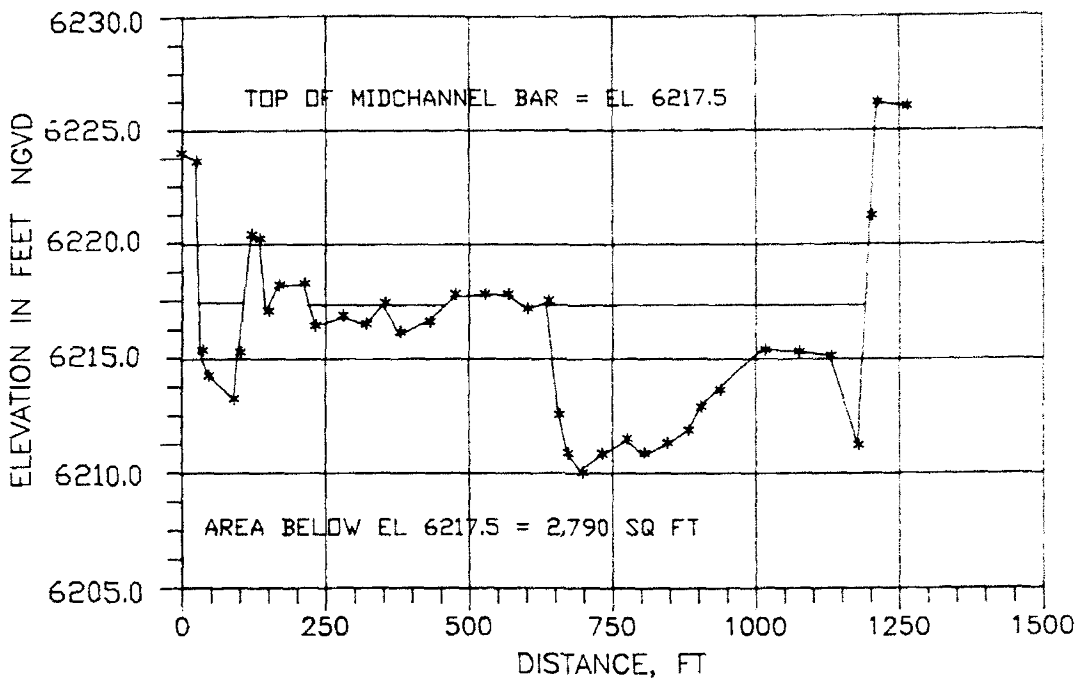
STA 7+05



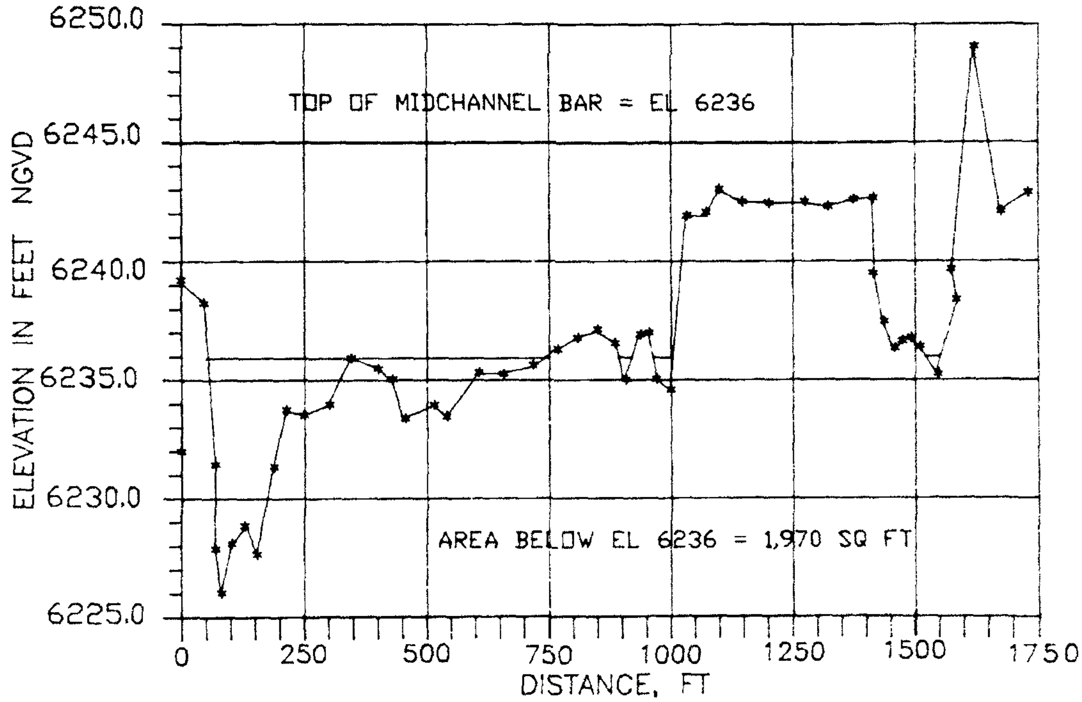
STA 7+44

CROSS SECTIONS

STA 7+05 AND 7+44



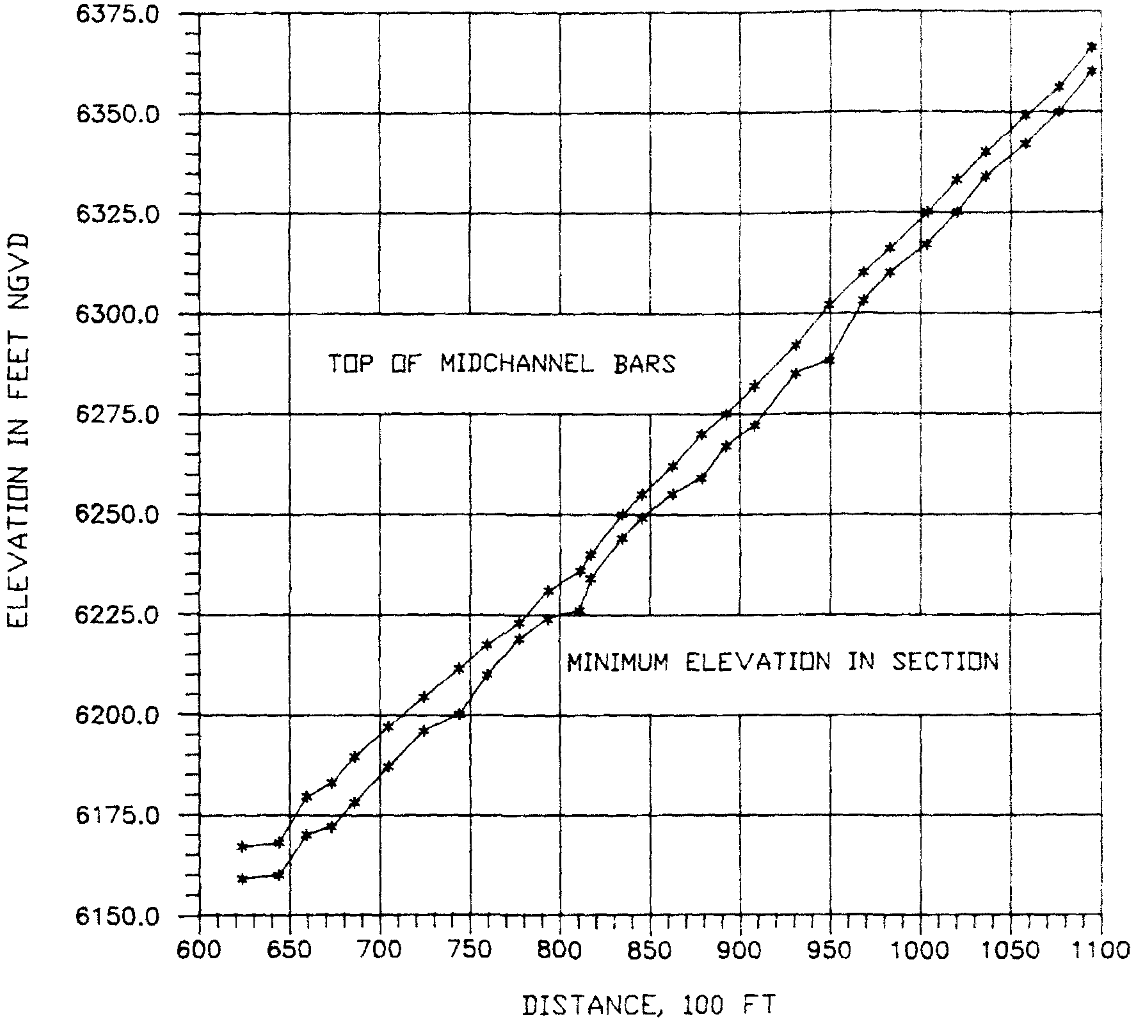
STA 7+60



STA 8+11

CROSS SECTIONS

STA 7+60 AND 8+11



TOP OF MIDCHANNEL BARS AND MINIMUM ELEVATION

REPORT DOCUMENTATION PAGE

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OMB No. 0704-0188

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Stephen T. Maynord

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13. ABSTRACT *(Maximum 200 words)*
Flow impingement occurs when approach channels direct flow into a bank line at large acute angles. Flow impingement results in flow concentration along bank lines, which creates large forces on bank material or bank protection. As part of studies conducted to determine the required riprap size for impinged flow, velocities, water-surface elevations, and scour depths were measured on the Snake River near Jackson, WY. High velocities and steep water-surface slopes were observed at each impingement site.

14. SUBJECT TERMS
Bank protection — Riprap
Braided stream — Velocity
Flow impingement

15. NUMBER OF PAGES
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